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Research article

# Compact Z-pinch radiation source dedicated to broadband absorption measurements

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## Abstract

In order to acquire a broadband absorption spectrum in a single shot, a compact radiation source was developed by using a Z-pinch type electric discharge. This paper presents the mechanical and electrical construction of the source, as well as its electrical and optical characteristics, including the intense continuum of radiation emitted by the source in the UV and visible spectral range. It also shows that the compactness of the source allows direct coupling with the probed medium, enabling broadband absorption measurement in the spectral range of 200–300 nm without use of an optical fiber which strongly attenuates the light in the short wavelength range. Concretely, thanks to this source, broadband spectral absorption of NO molecules around 210 nm and that of OH molecules around 310 nm were recorded in this direct coupling arrangement. Copper atom spectral absorption around 325 nm of the peripheral cold zones of an intense transient arc was also recorded.

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*Keywords:* Z-pinch; Broadband radiation source; Broadband absorption spectrum

## 1. Introduction

Optical spectroscopy is a powerful technique to diagnose gaseous media, especially plasmas [1]. If the medium to be investigated emits very weak light, emission spectroscopy is no longer suitable and absorption spectroscopy is necessary. The latter requires an auxiliary radiation source which may be a tunable laser whose wavelength can be scanned to obtain an absorption spectrum [2]. In this case, the medium to be probed must be in the steady state or repetitive with a good reproducibility. When the medium to be probed is transient and has a very low repetition rate, the absorption spectrum has to be acquired in a single shot. This one-shot measurement therefore requires the use of a broadband radiation source which may be a black body, a flash lamp or even a source specially designed for intense radiation to perform absorption measurements, for instance, around 210 nm to measure NO molecules in the exhaust gases of an internal combustion engine [3], or around 310 nm for OH molecules in a combustion study, or around 325 nm for copper atoms in arcs using copper-containing electrodes.

Marketed black bodies typically have a temperature below 3000 K and emit very few UV photons. According to the Wien displacement law, a black body with a temperature below 3000 K has a maximum emission at a wavelength higher than 1000 nm, far from the UV range. On the other hand, a xenon flash emits UV photons, but produces many UV lines which make the absorption spectra in the UV range difficult to exploit. As for the deuterium lamp, the emitted light density is low.

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In a previous study, we developed a radiation source using a high-current electric discharge in a cylindrical tube at low initial pressure [4]. The discharge of the capacitor was triggered by a fast switch. The current begins to flow along the inner surface of the tube and generates an azimuthal magnetic field. In interaction with the current, the induced magnetic field creates a compressive force directed towards the axis of the cylindrical tube. This self-compression of the discharge, called the Z-pinch [5], generates a dense, high temperature plasma since when the current sheet collapses on the axis, the plasma becomes very dense due to a snowplow effect during compression, which drives all the particles towards the axis. In addition, the plasma temperature strongly increases as a result of the conversion of the current sheet kinetic energy into thermal energy at the moment of collapse, referred to as the pinch time. With appropriate initial conditions, the optical radiation of the plasma at the pinch time may be extremely intense and has a flat spectral continuum since the spectral lines are totally smeared out in the continuum background.

The source mentioned above was relatively large and could not be moved easily. Therefore, the light from this source was transported to the probed medium through an optical fiber, but an optical fiber strongly attenuates the light of short wavelengths around 200 nm. To avoid the need for an optical fiber, we developed a compact source directly coupled to the probed medium.

The use of a Z-pinch as broadband radiation source in the UV range is atypical. However the Z-pinch is widely used as a coherent radiation source in the EUV or soft X range. J.J. Rocca's team was the first to obtain the lasing at neon-like argon line at 46.9 nm thanks to the Z-pinch in an argon filled capillary [6]. Following this pioneering work, many teams have carried out experimental [7–11] and numerical [12,13] works on the Z-pinch in capillaries for the soft X laser effect.

The Z-pinch is mainly known as intense X-ray generator developed and studied in the context of thermonuclear fusion by inertial confinement. Several industrialized countries have their own large Z-pinches, and the best-known installation is certainly the one of the Sandia National Laboratories in the United States [14,15]. Motivated by the study of thermonuclear fusion and more generally the applications on high energy density physics (HEDP), other projects are developed, like the installation of PTS in China [16,17].

HEDP states generated either by the focusing of a high power laser on a target, or the ultra-fast electric discharge are very dense media. To diagnosis such medium, the absorption method is often used with a backlighter created for instance by focusing a laser beam on a thin metal foil [18] or by using an X-pinch [19]. Our source is designed for wavelengths of 200–400 nm which are far away from those necessary for HEDP diagnosis. In the case where one wants to adapt our compact source to generate photons of wavelength less than 150 nm, one should first replace the $MgF_2$ window by a device allowing the passage of energetic photons while maintaining the pressure in the tube. Assuming that the photons should be emitted in a vacuum space, a pinhole can ensure the interfacing between the tube and the vacuum [20]. In a similar situation where a pulsed discharge tube was installed on a several MeV/nucleon heavy ion beam line, two fast valves were used to isolate the tube and the vacuum and they were opened during the electrical discharge so that the interaction between heavy ion beam and plasma took place [21]. But the adaptation of such valve on our source will not be easy because of the difference in the tube volume and the time scale of the discharge. Once the interface is installed, operational parameters, such as the nature and the pressure of the gas, as well as the working voltage, must be optimized for the more energetic photons. According to works published on capillary discharge, it seems to us that one can obtain continuum band near 10 nm, but this latter may be superposed by lines from multi-charged ions.

In Section 2 of this paper, we present the mechanical and electrical construction of the compact source using the Z-pinch effect for intense radiation, as well as the electrical and optical characteristics of the source, including the intense continuum radiation in the UV and visible spectral range. In Section 3, we show that, thanks to this compact source, a broadband absorption spectrum of NO molecules around 210 nm, of OH molecules around 310 nm and of copper atoms around 325 nm can be obtained. In principle, these spectra can be used to determine the NO, OH and Cu concentration in each studied case, but these calculations are beyond the scope of this paper.

## 2. Compact Z-pinch radiation source

### *2.1. Mechanical and electrical construction of the compact source*

The electric discharge was created between two carbon electrodes set 10 cm apart, in a 5-cm-diameter quartz tube. A hole was drilled in the center of the electrodes to enable light output along the axis of the tube through two quartz windows placed at each end of the tube respectively. The window was mounted in a support which may be easily taken apart for cleaning. For wavelength shorter than 200 nm, quartz window was changed by $MgF_2$ window since the spectral transmission of this material is 94% down to 200 nm and about 50% at 125 nm. The light coming from the axis and limited by the small holes in the center of the electrode had a relatively low divergence, so that absorption measurements directly coupled with the probed medium could be carried out. When direct coupling is not required, it is preferable to use an optical fiber for the collection and transmission of light as it is more flexible.

A diaphragm pump was used to obtain first a primary vacuum in the discharge tube and then an optimal pressure of about 1 mbar depending on the working gas. The working gas flow was controlled by a Brooks 5850R mass flow controller. Gas circulated continuously in order to avoid pollution of the gas by particles ablated from the electrodes or the tube. Three working gases were tested, namely argon, helium and xenon.

As shown in Fig. 1, six capacitors with a capacitance of 1 μF each were arranged in a circle around the tube and were charged to a high voltage of 10–15 kV by using a high voltage

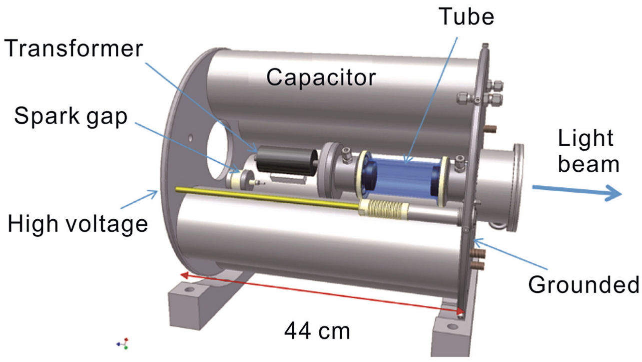


Fig. 1. Structure of the source including the tube, fast switch and six capacitors.

power supply (HVPS). The energy stored in the capacitors was 500 J at 13 kV. Thanks to the spark gap (EEV, series GTX), the energy previously stored in the six capacitors discharged quickly in the tube, producing a strong current whose peak value was close to 100 kA. In addition to the elements shown in Fig. 1, all the other necessary elements, i.e. the pump, gas flow regulator, HVPS, ROSS security relay, and electronic control board were placed in a mobile cabinet (see Fig. 2) with a standard width of nineteen inches.

Fig. 2. Grouping of all the necessary elements for the operation of the source.

## 2.2. Electrical characteristics of the source

Fig. 3 is the equivalent electric circuit of the source. To charge capacitor $C$ to a voltage of 15 kV with the HVPS, 15 s time was required. The repetition rate of this source was therefore limited to 4 shots per minute. To avoid overheating the source, we limited the repetition rate to 2 shots per minute.

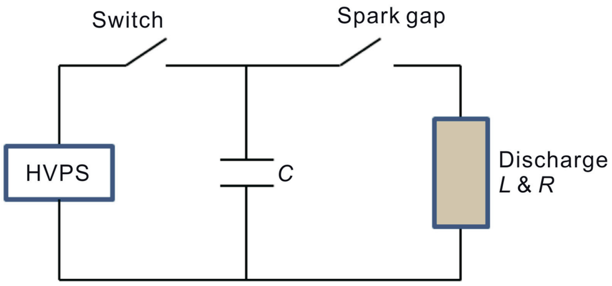


Fig. 3. After opening the switch on the left, the closure of the spark gap initiates the electrical discharge. The equivalent circuit of the discharge is a classical RLC series circuit.

Capacitor charging was controlled remotely via an optical fiber. When the voltage set value was reached, a signal of "end of charge" was generated to pre-synchronize the measuring instruments if necessary. The discharge was also remotely controlled via an order transmitted by another optical fiber. This order led to a closure of the Spark Gap, and hence to the discharge of the capacitors into the tube. Depending on the initial voltage and the initial pressure in the tube, the pinch time varied. However, for a given voltage and pressure value, the pinch time always occurred at the same moment with respect to the current onset. Thus, the current onset was used to synchronize the time resolved measurements, such as the measure of the radiation spectrum at different moments of the discharge.

In Fig. 4, the noisy curve is the time evolution of the discharge current measured with a Rogowski probe. The charging voltage was 13 kV and the argon pressure was 1 mbar. The current evolves according to the shape of a damped sinusoidal function similar to the current of a series RLC circuit given by Equation (1).

$$I = \frac{U_0}{L\omega} e^{-\frac{t}{\tau}} \sin \omega t \tag{1}$$

where $C$, $L$ and $R$ are the total capacity of the capacitors, inductance and resistance of the circuit respectively; $U_0$ is the

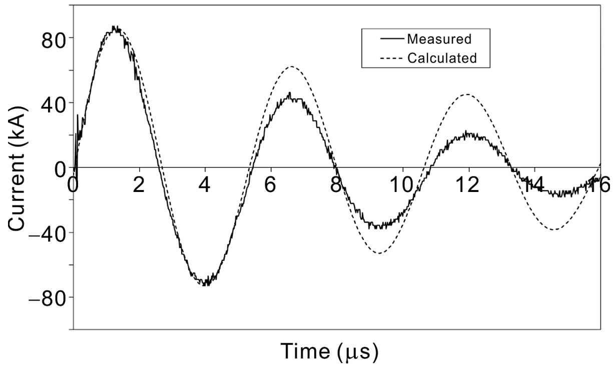


Fig. 4. Measured and calculated current without taking into account the temporal variation of the equivalent resistance of the circuit.

initial voltage across capacitors; $\tau = 2L/_R$ is the damping time constant and $\omega = \sqrt{\frac{1}{LC} - \frac{1}{\tau^2}}$ is the pseudo-angular frequency. Equation (1) is obtained by considering that the quantities $C$, $L$ and $R$ are constant. The dotted curve in Fig. 4 was calculated with Equation (1) using the following values: $\tau = 16.5$ μs, $C = 6$ μF, $L = 118$ nH and $R = 14$ mΩ. Comparing these two curves, there is a good agreement for the first cycle and the difference increases in time, no doubt due to the increase in resistance, leading to a stronger damping of the current.

### *2.3. Side-view of the plasma created by electrical discharge*

To maximally reduce the electromagnetic radiation, a cylindrical metal envelope (not shown in Fig. 1) was used to shield the discharge device. Without shielding, it was possible to observe the side of the discharge tube since there was a space between the two capacitors.

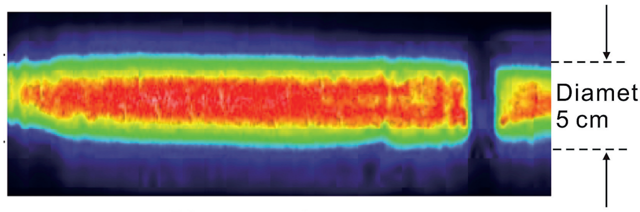
Photos were taken with an intensified CCD camera (Andor Technology) with 100 ns exposure time. Fig. 5 shows three photos taken at three different moments. For each photo, the intensifier gain was adjusted to avoid saturation, so the intensity of one photo cannot be compared directly with that of another. For each photo, the red part in the center corresponds to the discharge plasma, and the yellow area corresponds approximately to the quartz tube illuminated by the radiation from the plasma. The first picture was taken at the beginning of compression and the diameter of the plasma was about half that of the tube. The second photo was taken when the plasma had been well compressed, while the third one was taken at the pinch time, *i.e.* the moment of the maximum compression. The diameter of the plasma at the pinch time was about a tenth of the diameter of the tube, *i.e.* about 5 mm.

A streak camera was used to observe the dynamics of plasma compression. The image on the phosphor screen of the streak camera was recorded by a digital camera. In the picture shown in Fig. 6, the ordinate axis corresponds to the diameter of the discharge and the abscissa axis to the time. This picture made it possible to observe the compression of the discharge at the beginning of the discharge. As the source at the pinch time is very bright, a strong attenuation filter was used to avoid saturation of the image. As the light outside the pinch time is much lower, the discharge is only faintly observable in the photo. Two dotted lines were added to the photo to facilitate observation of the plasma compression in this photo. From the streak camera images, the duration of compression was estimated to be on the order of 100 ns, and the diameter of the discharge during maximum compression was estimated to be 5.5 mm, which is in good agreement with the observation made by using the ICCD camera image.

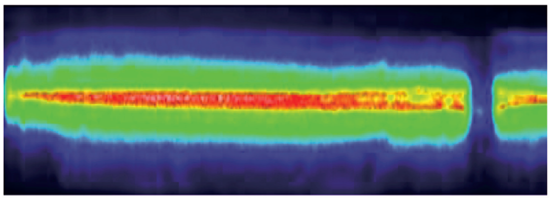
The pinch time depended on the initial voltage, the nature of the gas and its pressure. With a voltage of 13 kV and a mass flow of argon gas of 1 sccm, the maximum compression took place at 2.8 μs after the beginning of the discharge and the duration of the pinch time was estimated to be 200 ns, while for the case of xenon, the maximum compression took place at 5.6 μs and the duration of the pinch was estimated to be 400 ns.

### *2.4. Radiation of the compact source*

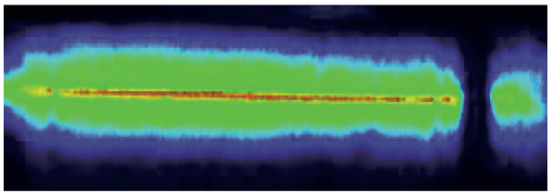
After installing the protective cylinder, light was collected along the axis of the discharge tube. This light was transported, via or not via an optical fiber, to a spectrometer for spectral analysis. Firstly, thanks to a Photomultiplier Tube (PMT), we measured UV light intensity versus time to verify that the radiation at the pinch time was very strong in



Picture at 2.5 μs



Picture at 2.7 μs



Picture at 2.8 μs (pinch time)

Fig. 5. Plasma pictures taken at three different moments by an ICCD camera. The diameter of the tube (5 cm) was indicated on the right side of the first picture. The origin of the time is the onset of the discharge current.

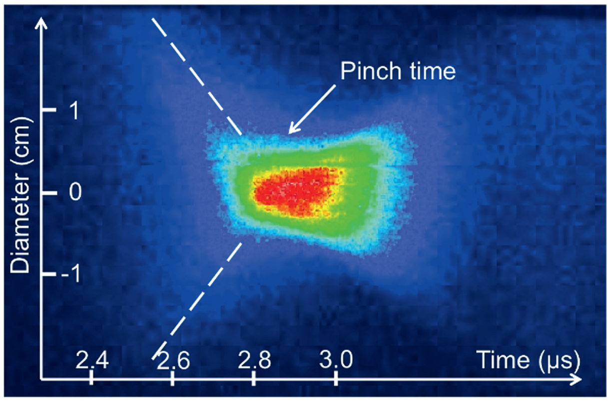


Fig. 6. Image given by a streak camera in the case of argon. The ordinate axis corresponds to the diameter of the discharge and the abscissa axis to the time. The origin of the time is the onset of the discharge current.

comparison to the other moments of the discharge. The measurement was made at the wavelength of 306 nm which is in the absorption band of OH. As a PMT gives a negative voltage whose absolute value is proportional to the light intensity, the negative giant peak of the PMT signal presented in Fig. 7 confirmed that the radiation, at least for the wavelength of 306 nm, was much more intense than that at other moments.

The spectrometer used was a Jobin Yvon TRIAX 320 with a focal length of 320 mm. An ICCD camera (Andor Technology) was used to record the spectra. To measure the radiation at the pinch time in the spectral range of 270–630 nm, 7 spectra were necessary because each spectrum only covers an interval of 60 nm. Figs. 8 and 9 provide spectral radiation of the plasma at the pinch time when the gas used was argon and xenon respectively. It can be seen that the spectrum emitted by xenon is smoother (fewer atomic emission lines); therefore xenon is more appropriate for the measurements of broadband absorption. However, the use of argon, helium or nitrogen is preferable due to their low cost compared to xenon if the quality of the radiation with these gases is good enough for a given broadband absorption measurement.

## 3. Broadband absorption measurements

### 3.1. Measurement in direct coupling

As mentioned in the introduction, we tested this source by making broadband absorption measurements of NO molecules around 210 nm. The experimental set-up is shown in Fig. 10. The compact source is on the right of Fig. 10, and a reactor dedicated to the study of combustion ignition was directly coupled with the radiation source. The TRIAX spectrometer is on the left of Fig. 10. An ICCD camera was installed at the focal plane of the spectrometer.

For this test, the combustion reactor was filled with NO diluted in argon. The NO concentration was 10,000 ppmv and absorption measurements were made with three different pressures, namely 0.2, 0.4, and 0.8 bar. The transmission spectrum was calculated from the absorption spectrum and the reference spectrum which was recorded without NO in the reactor just before and after the series of tests, since the source had an excellent reproducibility. Fig. 11 gives the spectral transmission for a total pressure of 0.2 bar. The exposure time of the camera for these acquisitions was 100 ns. This experimental curve can be fitted by a synthesized spectrum using for instance the Specair software [22], but as already mentioned, this fitting was beyond the scope of this study. In a previous study, the comparison between an experimental spectrum of

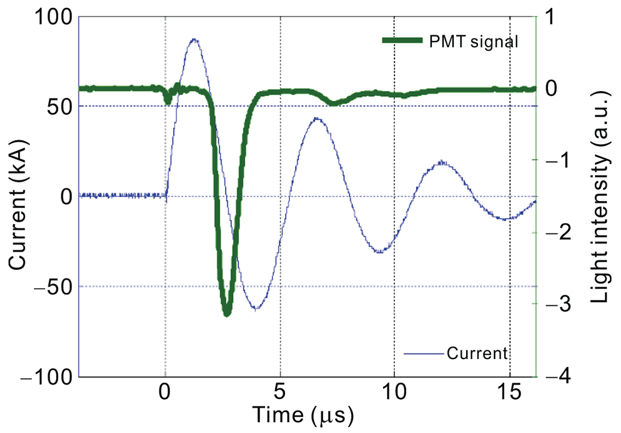


Fig. 7. Time evolution of the compact source emission at 306 nm measured by a PMT together with the discharge current. Experimental conditions: 13 kV and 1 sccm mass flow of Ar.

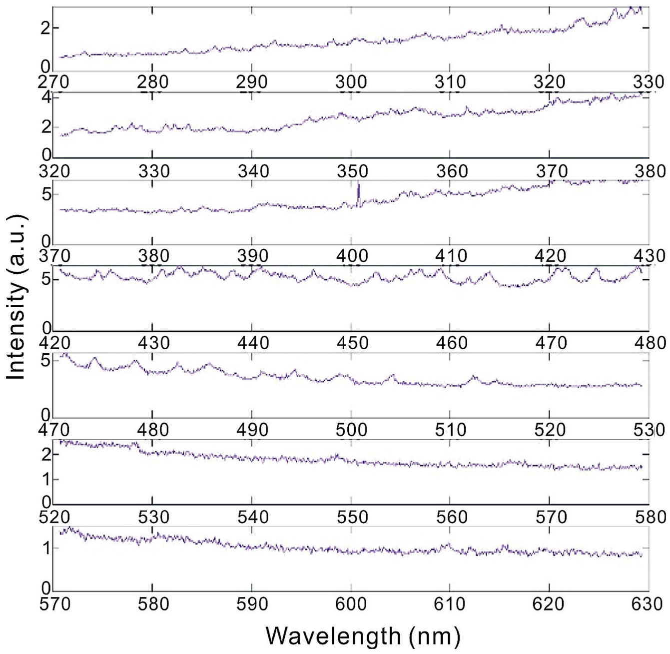


Fig. 8. Compact source radiation at the pinch time with argon gas.

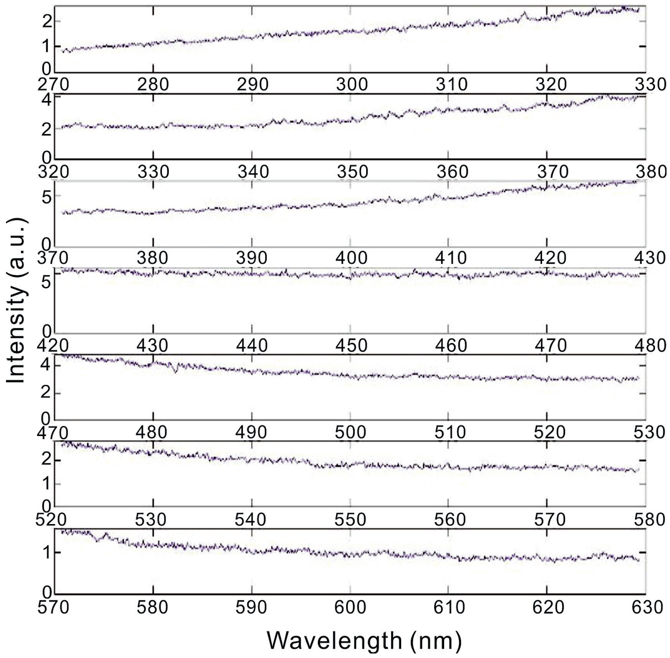


Fig. 9. Compact source radiation at the pinch time with xenon gas.

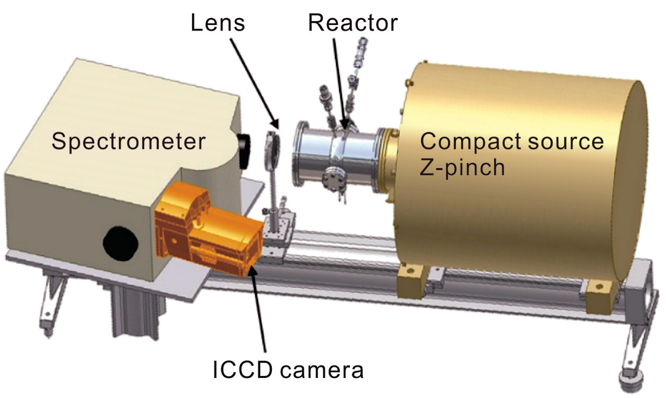


Fig. 10. Set-up for the broadband absorption measurement around 210 nm in direct coupling.

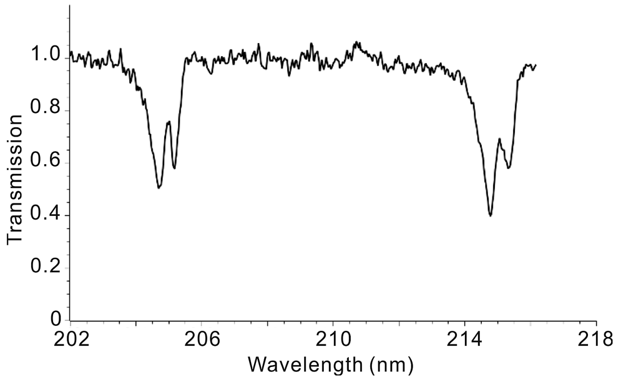


Fig. 11. Spectral transmission around 210 nm of a gas containing NO.

the $C_2$ Swan band and a synthesized one enabled the concentration of $C_2$ molecules in the investigated medium to be determined [4].

As absorption depends on the concentration, we performed measurements with two other pressures, 0.4 and 0.8 bar Fig. 12 presents all three spectra and shows that the higher the NO concentration, the greater the absorption.

As mentioned in the introduction, time-resolved OH absorption spectrum measurement is useful in combustion study. $CH_4$ and air were injected in a reactor and a spark was used to initiate a combustion in the reactor which generated OH molecules. Broadband absorption measurement was performed during the combustion and Fig. 13 gives the spectral transmission of the reactor at the measurement time due to OH molecule absorption during combustion.

### 3.2. Measurement using optical fibers

A study of a 200 cm long high-current arc was recently conducted [23]. To prepare that study, a preliminary experiment was performed on an arc of 10 cm long and with a 10 kA peak current value [24,25]. Few broadband absorption tests were performed with this arc of 10 cm in length. The arc was initiated thanks to the fusion of a copper wire initially connecting the two electrodes before the arc. There was thus a large amount of copper atoms in the plasma and in the peripheral zone of the arc. To quantify the concentration of copper in the plasma, emission spectroscopy can be used, while to determine the concentration in the peripheral zone of the arc, an absorption measurement is necessary. Given that the time between the two tests was more than 5 min, an absorption spectrum has to be recorded in a single shot and this measurement requires a broadband radiation source such as the one presented here.

Fig. 14 shows the experimental set-up without the Z-pinch source and the spectrometer which were placed far away from the arc. Two optical fibers were used to carry light from the source to the absorbing medium and from the absorbing medium to the spectrometer. These two fibers were placed face to face at a distance of 750 mm. As already mentioned, spectral transmission enables the determination of absorbing species concentration if the thickness of the absorbing medium in the direction of the beam is known. Because the arc in this study did not have a definite shape, a screen with a small opening was installed 75 mm from the electrode axis and the absorption measurement was made just behind the screen. In this case, the thickness of the absorbing medium was given by the width of the opening which was 19 mm.

Fig. 15 gives an absorption spectrum recorded at 3 ms after the beginning of the arc. This absorption spectrum makes it possible to calculate the concentration of copper

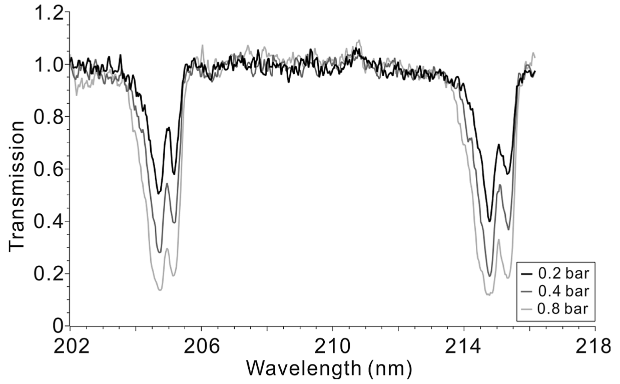


Fig. 12. Spectral transmission around 210 nm of a gas containing NO at three different pressures: 0.2, 0.4, and 0.8 bar.

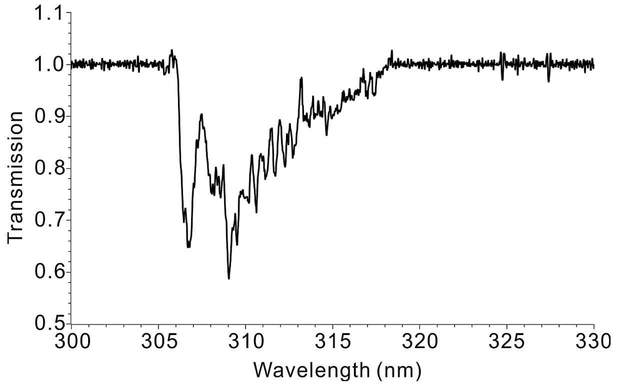


Fig. 13. Spectral transmission around 310 nm of a gas containing OH produced by $CH_4$ combustion.

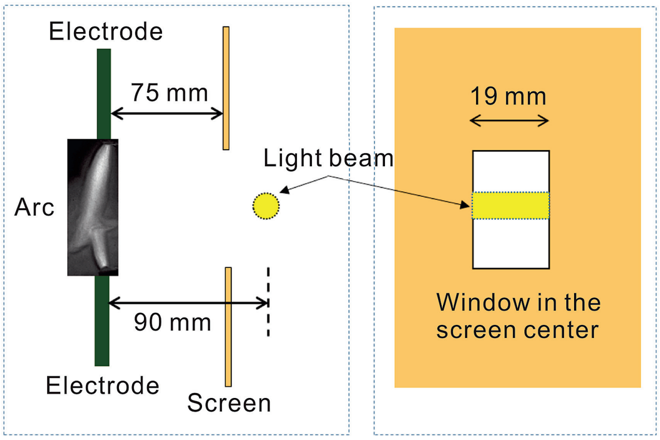


Fig. 14. Schematic sketch of the experimental set-up. The right side is the front view of the screen, showing the window and the light beam which was behind the screen.

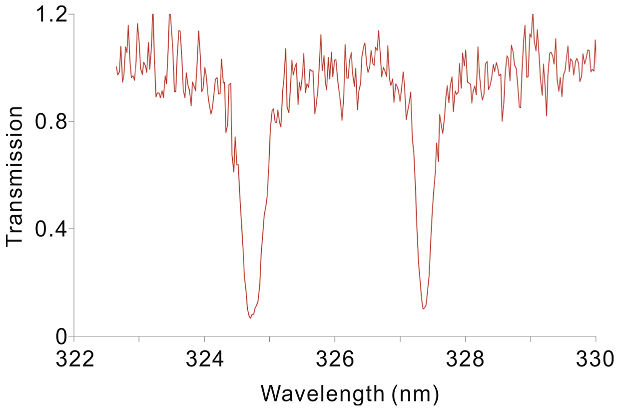


Fig. 15. Spectral transmission with 2 absorption lines of copper atom.

atoms in the ground state [4]. Since the measurement location is far enough away from the arc, the temperature must be low and the atoms in the excited state must be negligible. The total concentration is therefore the same as that of the ground state.

As the Z-pinch is very intense, the absorption measurement of the arc is possible in order to determine the population of some excited levels of copper atoms [26]. This measurement was not made since the thickness of the absorption medium was unknown due to the indefinite form of the arc in this study.

## 4. Conclusion

Electrical discharges are commonly used for light sources. Using the Z-pinch effect, we were able to make a particularly intense source and suitable radiation for broadband absorption measurements. The feasibility of this source to acquire absorption spectra has been demonstrated. The tests concerned broadband absorptions around 210 nm of NO molecules, around 310 nm of OH molecules and finally around 325 nm of copper atoms.

The exposure time in this study was 100 ns. This means that this source enables time resolved broadband absorption measurements in the sub-μs range.

Due to the use of quartz or $MgF_2$ window, the wavelength of light emitted from this source is limited to 200 nm or 150 nm respectively. Obtained photons are not energetic enough to probe the HEDP states. By using a suitable interface instead of the window, we are convinced that this source can produce a strong continuum towards 10 nm after optimization of the operating parameters.

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