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Induced m=0 instability in fast ablative capillary discharges and possible utilisation for X-ray lasers

Samir Ellwi,
Zeljko Andreic,
Sandrine Ferri,
Larissa Juschkin,
Konstantin Koshelev,
Hans-Joachim Kunze

Abstract High current linear discharges confined by their own magnetic field are subject to magneto-hydrodynamic instabilities which perturb a straight plasma column. An example is the m=0 mode, which is characterised by the development of necks contracting rapidly towards the axis with the ion sound speed. Discharges through capillaries were assumed to be stable hitherto, but by cutting capillaries lengthwise after a few shots hot spot traces clearly imprinted on the inner wall of the capillary are observed. They are interpreted as marks of an m=0 instability, and this interpretation is substantiated by a series of time-gated pinhole images, which show that the hot plasma region is clearly detached from the wall at the second current maximum and concentrated on the axis thus making the development of the instability possible. The instability occurs only with a specific sample of polyacetal as wall material, and its axial wavelength increases with the length of the capillary. By modulating respectively the inner wall of the capillary the wavelength can be imposed within limits. This is exploited for a soft X-ray laser scheme based on charge exchange pumping of bare carbon ions of hot plasma streaming from the necks and colliding with cold plasma outside the neck regions. Exponential growth of the Balmer-α line of CVI at 18.22 nm is realised.

Key words Balmer-alpha of CVI • capillary discharge • charge exchange • induced instability • X-ray lasers

S. Ellwi, S. Ferri, L. Juschkin, H.-J. Kunze✉
Institute of Experimental Physics V,
Ruhr-University, 44780 Bochum, Germany,
Tel.: +49 234/ 3225785, Fax: +49 234/ 3214175,
e-mail: Hans-Joachim.Kunze@ep5.ruhr-uni-bochum.de

Z. Andreic
Institute of Experimental Physics V,
Ruhr-University, 44780 Bochum, Germany
Permanent address: Division of Materials Research,
Rudjer Boskovic Institute,
Bijenicka 54, 10000 Zagreb, Croatia

K. Koshelev
Institute for Spectroscopy, Russian Academy of Sciences,
Troitsk, Moscow region, 142190 Russia

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Introduction

Fast capillary discharges were known as incoherent radiation sources in the EUV and soft X-ray spectral regions for some time and have recently attracted renewed interest as discharge-pumped short-wavelength lasers. They may be divided into gas-filled systems, which typically have diameters of several millimetres, and ablative capillaries of diameters one millimetre and less where the discharge medium is provided from the wall by an initial sliding discharge along the wall. At high currents, pinching of the plasma column may occur but material from the wall usually still surrounds the plasma column and thus stabilises possible sausage-type instabilities [4]. During investigations of such a setup for lasing on the Balmer-α line of CVI at 18.22 nm an unexpected instability at the second current maximum was identified, which was essential for lasing [3]. The instability manifested itself as a short perturbation on the current derivative, as a short intensity burst on the above Balmer-α transition exactly at the same time, and as imprints on the capillary wall, discovered when the capillary made of polyacetal was cut lengthwise after use. Typical values were $ka_0 \approx 2.5$ for a capillary 1 cm in length, where k was the axial wave number of the instability deduced from the imprints on the wall, and a_0 was the radius of the capillary, several capillaries of different diameter having been investigated. This is very close to the modes with $ka \approx 1$, for which theory predicts maximum growth rates, a now being the radius of the plasma column at the onset of the instability. Capillaries 2, 3 and 5 cm in length yielded ka_0 values of 1.6, 0.8, and 1.2, respectively.

This decrease of the axial wave number and thus increase of the wavelength of the instability for longer capillaries was harmful to our goal of an X-ray laser and prompted the present studies.

Experimental setup

A complete description and a schematic representation of the experimental setup will be published elsewhere. Here only a brief introduction to the experiment is given. Both discharge electrodes are made of tungsten and have an axial bore. Five capacitors of 20 nF arranged in the shape of a star are connected directly to the capillary arrangement, the capillaries being made of polyacetal. The current derivative dI/dt is recorded by a shielded Rogowsky loop. Time resolved spectra are obtained with a 1 m grazing incidence spectrometer combined with a NE111 plastic scintillator (exit slit of 200 μm) linked to a photomultiplier (Hamamatsu R2496) by fiber optics. A pinhole camera of square shape 100×100 μm is used. The pinhole is covered with an aluminium filter 0.2 μm thick. The images are recorded with a combination of a microchannel plate (MCP) and a CCD camera at a magnification of 2.42. The size of one pixel corresponds to 15.5 μm, the gating time is variable and was set to 5 ns in the studies discussed in the following sections.

Results and discussion

Initially all previous observations of Ref. [3] could be verified. Fig. 1 shows the current of the discharge and the emission of the Balmer-α line of CVI at 18.22 nm as a function of time for a straight capillary of 5 cm in length. The large emission spike is taken as the time marker for the instability. It always occurs at the time of the second current maximum, the jitter being a few nanoseconds. For shorter capillaries, the circuit inductance becomes lower, the discharge period shorter, and the instability occurs earlier correspondingly, always remaining at the current maximum. This obviously indicates similarities with a fiber initiated Z-pinch, which also remained stable until reaching current maximum [5]. In the ablative capillary the first half cycle is needed just to provide the initial homogeneous plasma. Stabilisation by material from the wall does not occur since the pinch column indeed detaches sufficiently well from the wall in all cases when the instability develops as will be shown below.

Haines and Coppins [1] present a universal stability diagram and discuss that Z-pinches should be stable for Lundquist numbers S below a critical Lundquist number given by $S^* \approx 50(ka)^{-0.86}$. S depends strongly on the current I and the line density N ($S \sim I^4/N^2$), and it is estimated for our plasmas produced from polyacetal to be around and above the critical Lundquist number at the second current maximum. The m=0 mode thus indeed is possible, but it certainly may not occur if too much material is ablated during the first half cycle resulting in a line density too high and a current too low in the second half cycle because of stronger damping of the discharge.

For our X-ray laser scheme it is essential that the instability develops uniformly along the axis, i.e. that specifically all neck regions are produced exactly at the same time to within less than one nanosecond, and that the wavelength of the instability does not increase with the length of the capillary as observed previously [3]. We induced, therefore, successfully the instability by modulating the inner wall of the capillary (waved capillary) and thus imprinting a wave structure onto the surface of the plasma column. In this way we succeeded to have shorter wavelengths also for longer capillaries.

Straight and waved capillaries were made and tested from ten samples of polyacetal, but only one sample was useful and the instability developed. This reveals how crucial the wall material is in providing the right plasma during the first half cycle. This also explains why the effect has not been observed by other researchers. The growth time of such an instability is connected to outflow of plasma from the neck regions, and it is typically of the order of a/c_S, where c_S is the ion sound speed. The high temperature phase of the instability, however, is much shorter and is typically of the order of 1 ns [6, 7]. This is comparable to the duration of the observed spike of the Balmer-α line of the CVI at 18.22 nm.

It is also important to mention that in all cases where no spike was seen, also no traces of an instability imprint on the inner wall of the capillary was observable. This spike will be explored later in this paper to show the relation

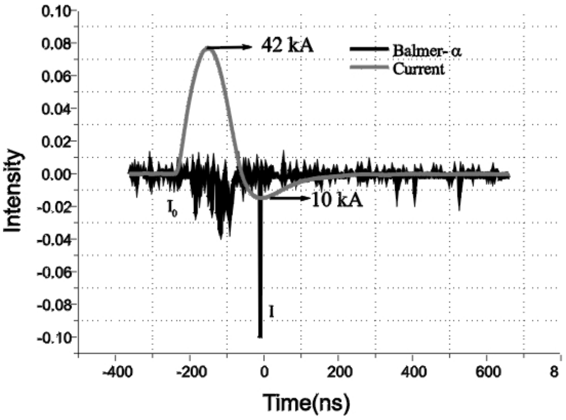

Fig. 1. Balmer-α transition of CVI and current as a function of time for a straight capillary of 50 mm length and 0.7 mm diameter. The emission was recorded using the photomultiplier mentioned earlier in the setup.

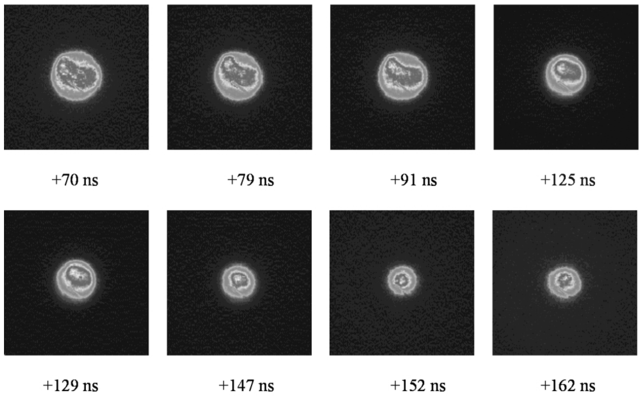
+70 ns
+79 ns
+91 ns
+125 ns
+129 ns
+147 ns
+152 ns
+162 ns

Fig. 2. Pinhole images of the capillary taken at different times of the discharge.

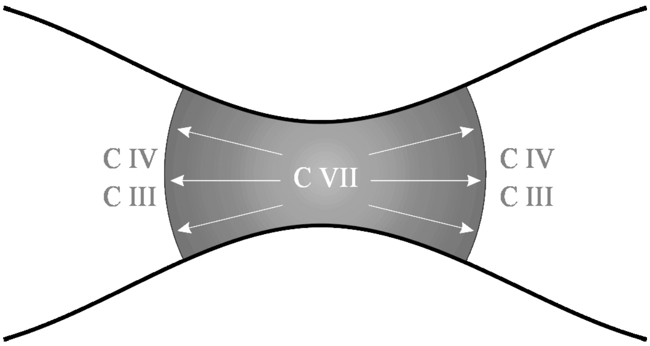

Fig. 3. Scheme of a neck type instability.

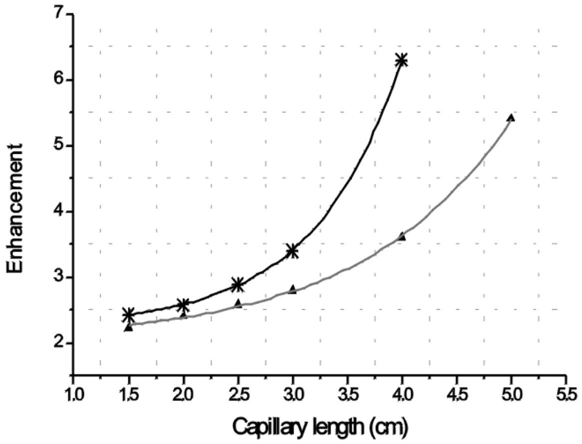

Fig. 4. Enhancement of the Balmer-α line of CVI as function of capillary length for two different waved capillaries with * 0.8 mm and ▲ 1.0 mm inner diameter.

between the MHD instability and X-ray laser signals. Time-gated pinhole images now also support the existence of such an instability. As shown in Fig. 2, at a time of 152 ns from the beginning of the discharge, which corresponds to the time of the second current maximum, the plasma is completely detached from the wall and the hottest region is localised at the centre of the image. The time resolution of the MCP being around 5 ns certainly limits the achievable spatial resolution. In all cases of no instability, the detachment from the wall is indeed less pronounced.

We utilise the instability and in particular the hot plasmas of the neck regions for our X-ray laser scheme. The short emission spike is observed only at one wavelength, i.e. only on the Balmer-α line of CVI indicating a highly selective population mechanism. In addition, the spike increases with the length of the capillary. Without inducing the instability this increase was only linear due to the increase of the axial wavelength of the instability thus obscuring lasing. The induced instability now provides exponential growth as is characteristic of lasing. We propose charge exchange between bare C^{6+} ions and C^{2+} ions as effective population mechanism leading to the overpopulation of the n=3 level of the hydrogenlike ion CVI. The bare nuclei are readily produced in the neck regions of the instability, only temperatures of about 150 eV are necessary. These ions stream out of the necks into the cold plasma outside the necks at typical velocities of 10^7 cm/s equivalent to a kinetic energy of about 600 eV, and they collide with plasma particles such as electrons, protons and carbon and oxygen ions. A simplified model of the geometry is shown in Fig. 3. The charge exchange recombination with CIII has a very high cross section into the n=3 level of CVI resulting in population inversion. At both sides of each neck an inversion layer is thus created for a short time resulting in a column of inversion layers along the axis [2, 3].

Inducing the instability now offers the possibility of manipulating the axial wavelength of the instability and hence the number of inversion layers. Several wavelengths were tested, a wavelength of 0.8 mm proved to be an optimum. It is probably not surprising that it is close to the naturally occurring wavelengths in the capillary. Now indeed a true exponential growth of the emission spike of the Balmer-α line CVI with capillary length is observed since the number of inversion layers per unit length is kept constant. Fig. 4 shows examples of two capillaries with different inner diameters. The occurrence of the instability thus indeed can be manipulated within certain limits.

Confirmation of lasing was made by placing a multilayer mirror of 30% at one end resulting in a pronounced increase of the spikes. The average magnitude of the spikes increased by a factor of 2 for a capillary of 30 mm, which is quite consistent with previous measurements.

Conclusions

In conclusion, our results clearly show that the m=0 instabilities in the ablative capillary discharge can be induced and thus all constrictions made to grow reliably at the same time provided, of course, that correct plasma conditions exist. Charge exchange recombination between the hot carbon plasma in the neck regions and the cold plasma outside is successfully employed for lasing on the Balmer-α transition of CVI at 18.22 nm.

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References

1. Haines MG, Coppins M (1991) Universal diagram for regimes of Z-pinch stability. Phys Rev Lett 66:1462–1465
2. Koshelev KN, Kunze H-J (1997) Population inversion in a discharge plasma with neck-type instabilities. Quantum Electron 27:164–167
3. Kunze H-J, Koshelev KN, Steden C, Uskov D, Wieschebrink HT (1994) Lasing mechanism in a capillary discharge. Phys Lett A 193:183–187
4. Schefel J, Coppins M (1993) Reconsideration of the m=0 Z-pinch stability. Nucl Fusion 33:101–115
5. Sethian JD, Robson AE, Gerber KA, DeSilva AW (1987) Enhanced stability and neutron production in a dense Z-pinch plasma formed from a frozen deuterium fiber. Phys Rev Lett 59:892–895
6. Vikhrev VV, Ivanov VV, Rozanova GA (1993) Development of sausage-type instability in a Z-pinch plasma column. Nucl Fusion 33:311–321
7. Yan’kov VV (1991) Z-pinches. Sov J Plasma Phys 17:305–311