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# Application of the digital imaging technique using IMACON 790 camera for compression plasma flows investigation

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**The results of application of the technique for digital image acquisition using an ultra-high-speed camera on the magnetoplasma compressor discharge investigation are shown. The principal working regimes of quasi-stationary compression plasma flows at low and high pressures were studied. Temporal development of discharge: breakdown, shock wave formation and compression plasma flow and plasma quenching were analysed. The basic plasma parameters: velocity, plasma flow dimensions and discharge phases duration were measured. The velocity of compression plasma flow microstructures was determined from the streak records in hydrogen, argon and nitrogen within the 10 - 50 000 Pa pressure range. The highest plasma velocities 100-120 km/s, were measured in hydrogen at 1000 Pa.**

*Key words:* **ultra-high-speed camera, digital image acquisition, velocity measurement, plasma, magnetoplasma compressor.**

## Used marks and symbols

| | |
|---|---|
| $v$ | - velocity, m/s |
| $v_z$ | - streak speed (time per lenght unit), s/m |
| $k$ | - image/object reduction factor |
| $\alpha$ | - tangent slope angle to streak curve. |

## Introduction

THE Imacon 790 ultra-high-speed converter camera is used for plasma recording in two modes which enable space and time investigations of the phenomena development. Owing to high-time magnification, the camera gives detailed visual information and simultaneously enables quantity measurements (phenomena duration, lenght, and velocity). The lack of Imacon camera films resulted in a new recording technique development, based on the existing camera adaptation. The new technique gives a digitized record suitable for further processing, as well as measuring and storing of relevant quantities. The plasma formed in the magnetoplasma compressor (MPC), an acceleration-compression plasma system in which high-energy and quasi-stationary compression plasma flows were produced [1-4], was investigated by using this recording technique.

Previous investigations of MPC plasma parameters were carried out in hydrogen within the 500-1000 Pa pressure range, and argon was added for spectroscopy mesurements [4] only. The MPC discharge phases were analyzed in detail and the plasma parameter measurments in wide pressure interval (10-50 000 Pa) with different working gases (hydrogen, argon and nitrogen) were calculated by using the digital imaging technique. Particularly important were the visual insight into the plasma compression flow structure and the plasma velocity measurements in that field.

## Experiment set-up

The compact geometry magnetoplasma compressor (MPC-CG), investigated in this paper, is shown in Figure 1. The iner electrode (cathode) is made of copper and is conically shaped with a hole on the peak (divertor). The cylindrical outer electrode (anode) is made of eight copper rods (0.8 cm in diameter and 14 cm in length), symmetrically positioned along the circle of 5 cm in diameter.

The MPC-CG enables plasma flows forming with a discharge current of 70 - 100 kA. The plasma source is placed in a vacuum chamber. The described experiments were performed in a residual gas regime, within the 10-50 000 Pa pressure range. A two-stage mechanical vacuum pump is used to deflate the vacuum chamber below 1 Pa. Different working gases to the given pressure are then introduced into the chamber*. The pressure was measured by the mechanical and Leybold-Heraeus pressure meters. Working gases were hydrogen, argon and nitrogen.

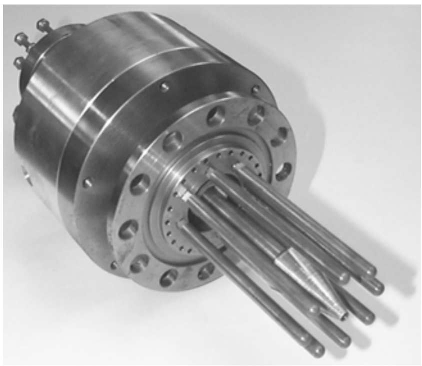

**Figure 1.** Compact geometry magnetoplasma compressor

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The experiment set-up used is schematically presented in Figure 2. The electrode system is connected to the 800 μF capacitor bank (C) through the IRT-6 ignitron (I). Trigger signal is fed to the ignitron. Maximal discharge current is 40-100 kA with the condenser voltage from 2.5 kV to 4.1 kV. The capacitor bank, charged from the GOS 1001source, has the repetition rate of 1-2 shots per minute.

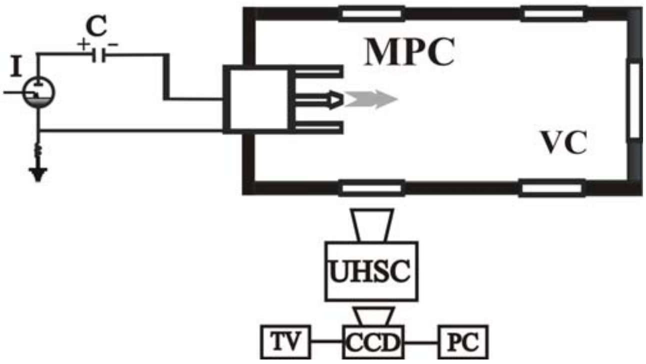


**Figure 2.** Experiment set-up: MPC - magnetoplasma compressor, VC - vacuum chamber, C - capacitor bank, I - ignitron, UHSC - ultra-high-speed camera, TV - television set, CCD - video camera, PC - personal computer.

The Imacon 790 ultra-high-speed camera (UHSC) was used for the MPC investigation. The imacon is an electronic converter camera with highlight gain, which forms a record on the output phosphor screen [5]. The camera can work in two modes: the framing mode - frame by frame and the streak mode - continual recording. In the framing mode two rows of succesive frames are produced on one image. Interframe time is the framing speed reciprocal, the exposure of each frame being 1/5th of that interval. Framing speed is determined by the framing unit used for recording. For the MPC recording the framing speeds of $1\times10^5$ and $5\times10^5$ frames/s with interframe intervals of 10 $\mu$s and 2 μs, and the exposure per frame of 2 $\mu$s and 400 ns are respectively. The number of frames, from 8 to 16, is selected before recording. Frame format is 16 mm x 18 mm (8 frames ) or 8 mm x 18 mm (16 frames ). For its clearness and explicity the framing record is suitable for observing space and time discharge development. It serves for discharge phases identification and their duration determination, measurements of compression flow dimensions and duration, as well as for comparison of those characteristics for different working gases.

In the streak mode the image is optically restricted by a mask with a slit in such a manner that only a thin section of the chamber with the MCP is observed. This narrow band is then moved across the camera output screen with a constant speed determined by the used streak unit, i.e. by the unit streak speed ($v_z$). The velocity measurement method [6], in which the event velocity vector is parallel to the streak slit and perpendicular to the optical axis of the camera (Fig.3) is applied. The slit position related to the electrode system of MPC is indicated in Figure 4. A continual record, which shows the plasma displacement along the slit direction versus time (Fig.3), is obtained on the Imacon camera output screen time. The streak record dimension is 70 mm (horizontally) x 18 mm (vertically).

For the MPC recording two streak speeds ($v_z$) of 500 ns/mm and 1 $\mu$s/mm, with total recording time of 35 $\mu$s and 70 μs, were used respectively. As the streak speed differs from the value shown on the unit indicator, real streak speed of each used streak unit has to be determined by calibration. The Hadland Photonics pulse delay generator model 103 is used as a calibrator with calibration frequences from 1 kHz to 10 MHz. The slit width is 100 $\mu$m for all recordings. As the streak record produces a continual image, it enables the breakdown point determination, clear time positioning of the plasma shock front and compression flow, visual observation of plasma compression flow structures and determination of microstructures frequency, as well as the measurement of the shock front and compression flow velocity. Both velocities are determined by the same streak record using eq.(1) [7]:

$$v = \frac{tg\alpha}{k \cdot v_z} \tag{1}$$

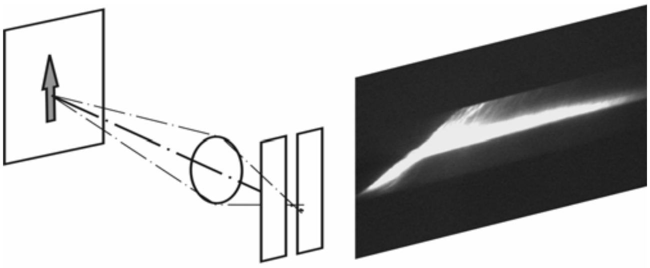


**Figure 3.** Velocity measurement method

In both recording modes the camera is used in lateral position. In the framing mode, due to extensive geometry of the event, that position is convenient for obtaining 10 to 12 frames on one image instead of only 8. In the streak mode, lateral position is necessary for the application of the velocity measurement method shown in Figure 3. Neutral filters are used in order to recognize details and increase image sharpness. In this way plasma compression flow microstructures are noticed in streak records.

Synchronization between the MPC discharge breakdown and the start of recording is carried out by the use of the battery powered Imacon fast photocell. Time scanning in the framing mode is performed using the Hadland Photonics delay generator model 103.

Images are recorded on the Polaroid film type 667 placed in direct contact with the Imacon output screen. The record was subsecuently digitized for further processing by means of a scanner with 400 dpi. As a result of the lack of films and need for recording in digital form, a new recording technique was developed during this experiment. Instead of film, a CCD video camera connected to personal computer is used, giving images in digital form during recording [8]. The Mintron OS 45 D video camera with 795x596 picture elements, resolution of 600 TV lines horizontal and gamma set to 1 was used. The video camera is mounted on the support bracket and optically coupled to the Imacon output screen, both placed inside a dark chamber at the back of Imacon. A CCD analog video out is led to the MiroVideo DC 30 card. The video card performes digitization of input data and storage in memory as an AVI file. The Adobe Premiere 5.1 film processing software displays a video sequence divided in frames recorded by video camera. The Imacon image represents one frame which is separated from the video sequence after recording. TV set connected to a CCD camera is used for visual control during recording (Fig.2). Black and white video camera is used because of higher resolution, better signal/noise ratio and higher sensitivity and contrast compared to color video camera. Exposure time for video camera is not critical considering that the Imacon output phosphor persistence is 80 $\mu$s.

## Results

Based on UHSC records, two MPC working regimes were established depending on working gas pressure. The regular acceleration - compression regime is formed as a dominant one at low pressures up to 3000 Pa. The deceleration regime exists at higher pressures.

### *Acceleration - compression regime*

MPC acceleration - compression regimes in argon, nitrogen and hydrogen were investigated in detail, from minimal breakdown pressures up to 3000 Pa. In this experiment the capacitor bank voltage was constant (4 kV). Although the

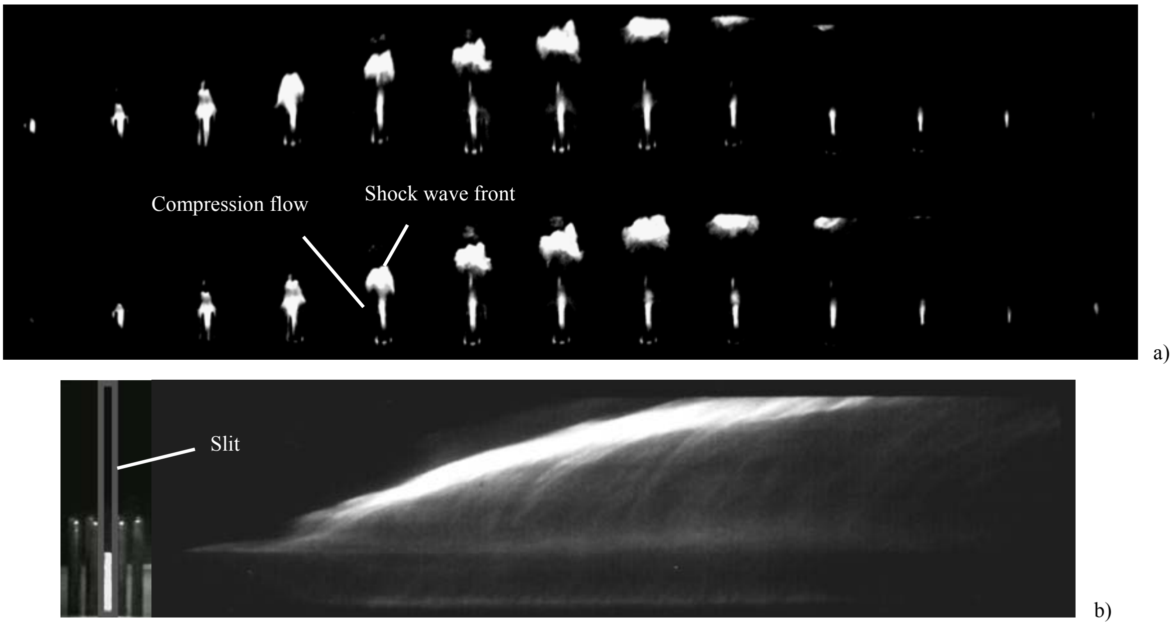


**Figure 4.** a) MPC discharge development shown with the interframe interval of 2 $\mu$s and the exposure per frame of 400 ns (Ar, 100 Pa, 4 kV); b) streak record at 1 $\mu$s/mm (Ar, 100 Pa, 4 kV); left: MPC with the camera slit

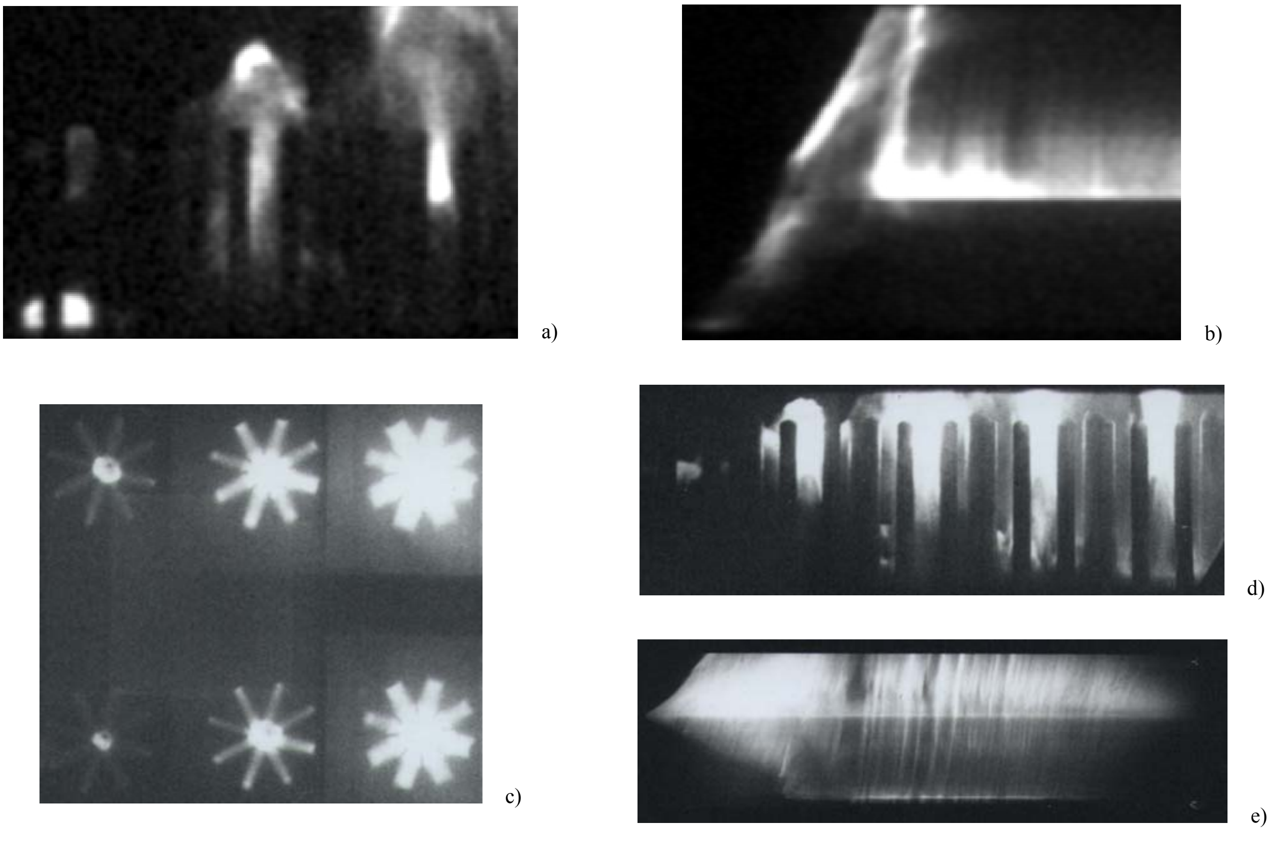


**Figure 5.** Breakdown developments from: a,b) the widest conical cathode part (N2, 1000 Pa, 4 kV); c,d,e) the top of the cathode (Ar, 100 Pa, 4 kV). Framing records a,d) side-on (frames at 4 $\mu$s with the exposure of 400 ns), and c) end-on observation (frames at 500 ns with the exposure of 100 ns). Streak records b,e) at 1 µs/mm; white arrows point to the top of the cathode

MPC-CG discharge development depends on the initial conditions such as the type of working gas, pressure and input energy, it has been found, on the bases of UHSC images (Fig.4), that the following general picture of the dynamics of the compression plasma flow formation can be obtained. The discharge development can be divided into four phases.

The first phase starts with the ignitron triggering and discharge breakdown in the MPC inter-electrodes region and lasts until the plasma exits that region.

Based on UHSC records, it has been found that in all gases at high pressures the breakdown starts from the widest conical cathode part (Fig.5a,b). However, below particular pressure value (for instance in nitrogen and argon ~100 Pa) the breakdown starts from the top of the cathode (Fig. 5c,d,e). At pressures below 200 Pa, the breakdown in hydrogen also starts from the top of the cathode. At the pressure of 3000 Pa the breakdown starts from the widest breakdown cathode part and the shock wave reaches the top of the cathode in 20 $\mu$s, 12 $\mu$s and 6 $\mu$s in argon, nitrogen and hydrogen, respectively. This interval is reduced with the pressure decrease and at 1000 Pa lasts 12 $\mu$s, 8 $\mu$s and 4 µs in argon, nitrogen and hydrogen, respectively.

The second phase starts with strong radial plasma compression at the top of the cathode and lasts as long as plasma oscillations exists. This transition phase precedes the quasistationary phase of the plasma flow. At the beginning of the second phase the plasma front rushes out as a shock wave. On the system axis, starting from the top of the cathode, the compression plasma flow is formed (Fig.4). When the breakdown starts at the widest conical cathode part, plasma is accelerated and when it reaches top of the cathode, the intensive plasma compression occurs - a shock wave pinch effect. At higher pressures, pinch lasts ~4 µs (Fig.6), and with the pressure decrease its duration diminishes and the pinch disappears.

The compression plasma flow becomes sustainable 10-20 µs after the beginning of the discharge. The fastest formation of compression flow occurs in hydrogen in which this process is completed in ~10 µs. Plasma compression results from the interaction between the longitudinal current component, which sweeps away from the discharge device, and the intrinsic azimuthal magnetic field. During this phase a ionization zone is established at the widest cathode part, i.e. in the region with the minimum cross-section of the acceleration channel (Fig.4,7). Within 15-30 $\mu$s significant radial oscillations of the compression plasma flow are noticed.

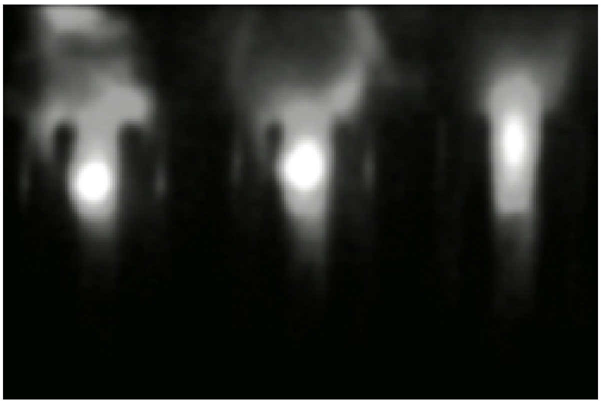
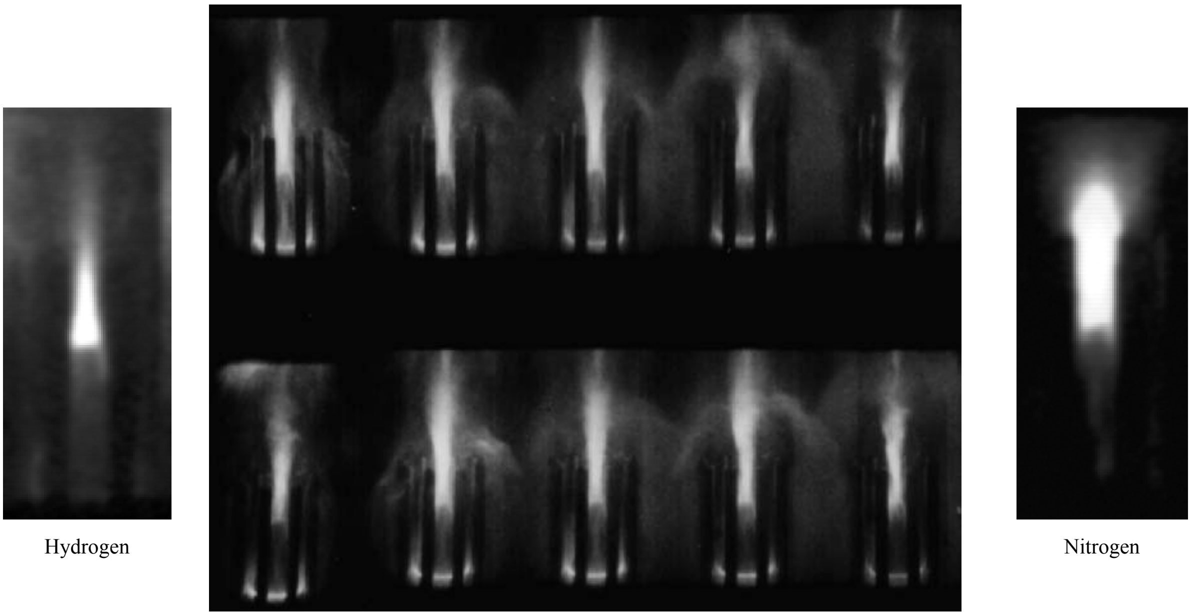


**Figure 6.** Pinch at the top of the cathode in nitrogen starting at 10 $\mu$s: frames at 4 $\mu$s

After termination of the described transient processes, the third, quasi-stationary phase starts, in which stable compression plasma flow exists. In Figure 7, the compression plasma flow in argon lasting 20 $\mu$s is shown. In the same figure, a stable ionization zone in critical cross-section can be noticed. The shape and duration of the compression plasma flow depend on type of working gas and its pressure (Fig.7-10), as well as on input energy. Within 30--70 $\mu$s, in hydrogen from 15 $\mu$s, plasma parameters are almost constant and the conditions for the local thermodynamic equilibrium (LTE) are fulfilled. The compression plasma flow duration increases with the pressure decrease.

In Figure 8-10 discrete microstructures of the compression plasma flow (light and dark regions) are observed. Fair microstructures are the plasma flow trajectory projections



Hydrogen

Nitrogen

Argon

**Figure 7.** A typical compression flow image in the quasi-stationary phase in argon, nitrogen and hydrogen. The MPC discharge development in argon shown at 2 $\mu$s, starting 20 µs after the beginning of the discharge

on the camera slit and these structures occur at frequencies of 5 - 10 MHz. In all gases at pressure of the 100 Pa order, plasma flow microstructures are very much expressed. The microstructure frequency increases with the pressure increase (Fig.8-10).

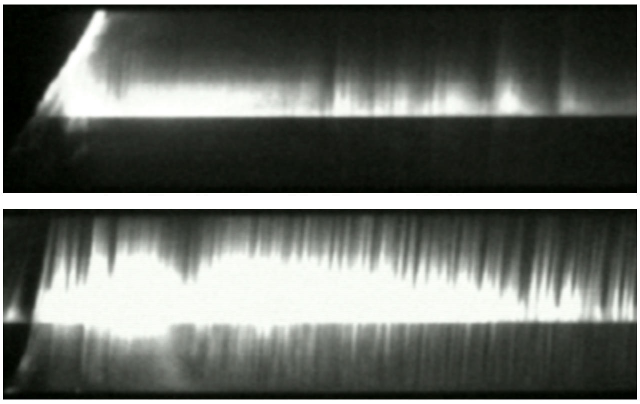


**Figure 8.** MPC discharge development in hydrogen at pressures of 1000 Pa (up) and 100 Pa (down): streak records at 1μs/mm

In hydrogen, the compression plasma flow duration at high pressures is 40-50 $\mu$s (Fig.8), and at low pressures (~100 Pa) the compression plasma flow duration is about 60 $\mu$s. At pressures higher than 1000 Pa the plasma shock wave velocity is 15 km/s and it increases with the pressure decrease (at 500 Pa the pressure shock wave velocity is 40 km/s). However, at pressure of 100-200 Pa the plasma shock wave, formed at the top of the cathode, moves slower (10-15 km/s). At pressures lower than 500 Pa, the compression plasma flow has length of the 3 cm order and the diameter of 0.3-0.5 cm (in the region of maximum compression). Length of compression plasma flow increases with the pressure decrease and at the pressure of 100 Pa the compression plasma flow length is 5.5 cm (Fig.8). The compression plasma flow velocities in quasistationary phase are measured using UHSC streak photographs by means of eq.(1). Plasma velocity in the 1000-3000 Pa pressure interval increases with the pressure decrease and the maximum value of plasma flow velocity (100-120 km/s, Fig.8) is observed at the pressure of 1000 Pa. At pressures lower than 1000 Pa the plasma flow velocity decreases with the pressure decrease and at the pressure of 100 Pa the plasma velocity is 80 km/s.

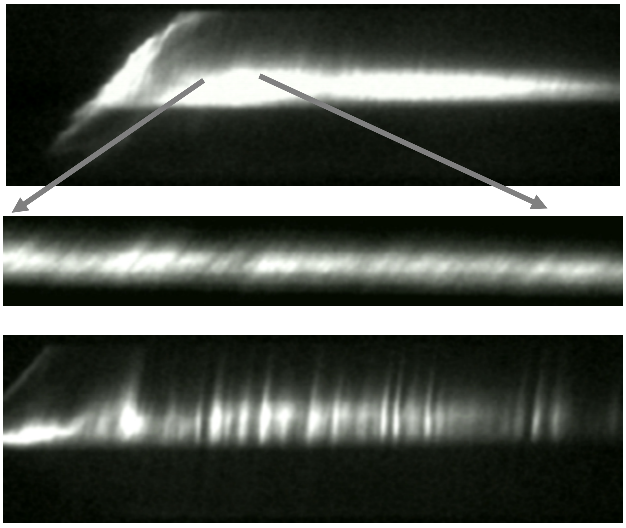


**Figure 9.** MPC discharge development in nitrogen at 1000 Pa (up and in the middle) and 100 Pa (down) pressures: streak records at 1 $\mu$s/mm.

In nitrogen, the compression plasma flow duration at high pressures is 30 $\mu$s (Fig.9), and at pressures of 100 Pa the compression plasma flow duration is about 40 $\mu$s. The shock wave velocity is 7-10 km/s at all pressures. The length of compression plasma flow at pressures higher than 500 Pa is of the 2.5 cm order, and the diameter of ~1 cm. The compression plasma flow length increases with the pressure decrease and at the pressure of 100 Pa length is 3.5 cm. The compression plasma flow velocity in nitrogen increases with the pressure decrease and at pressures higher than 1000 Pa the plasma velocity is 25 km/s, and at the pressure of 100 Pa the plasma velocity is 70 km/s.

In argon, the compression plasma flow duration at high pressures is 30 $\mu$s (Fig.10), and at low pressures (~100 Pa) the compression plasma flow duration is 40-50 $\mu$s. The plasma shock wave velocity is of the 5 km/s order at all pressures. The compression plasma flow length at pressures higher than 500 Pa is of the 4 cm order and the diameter in the region of maximum compression is 0.5-1 cm. The compression plasma flow length increases with the pressure decrease and at the pressure of 100 Pa the compression plasma flow length is 6 cm. The compression plasma flow velocity increases with the pressure decrease and at pressures higher than 1000 Pa the plasma velocity is 10 km/s, and at the pressure of 100 Pa the plasma velocity is 60 km/s.

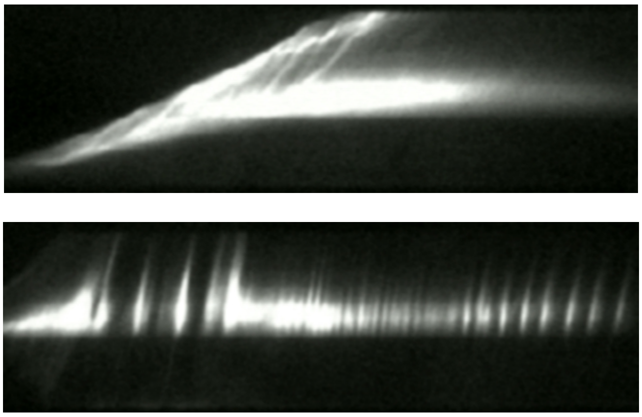


**Figure 10.** MPC discharge development in argon at 1000 Pa (up) and 100 Pa (down) pressures: streak records at 1 μs/mm.

Decreasing of the shock wave velocity and plasma velocity with the plasma departure from top of the cathode has been found in all gases at higher pressures because of the plasma deceleration in collision with buffer gas.

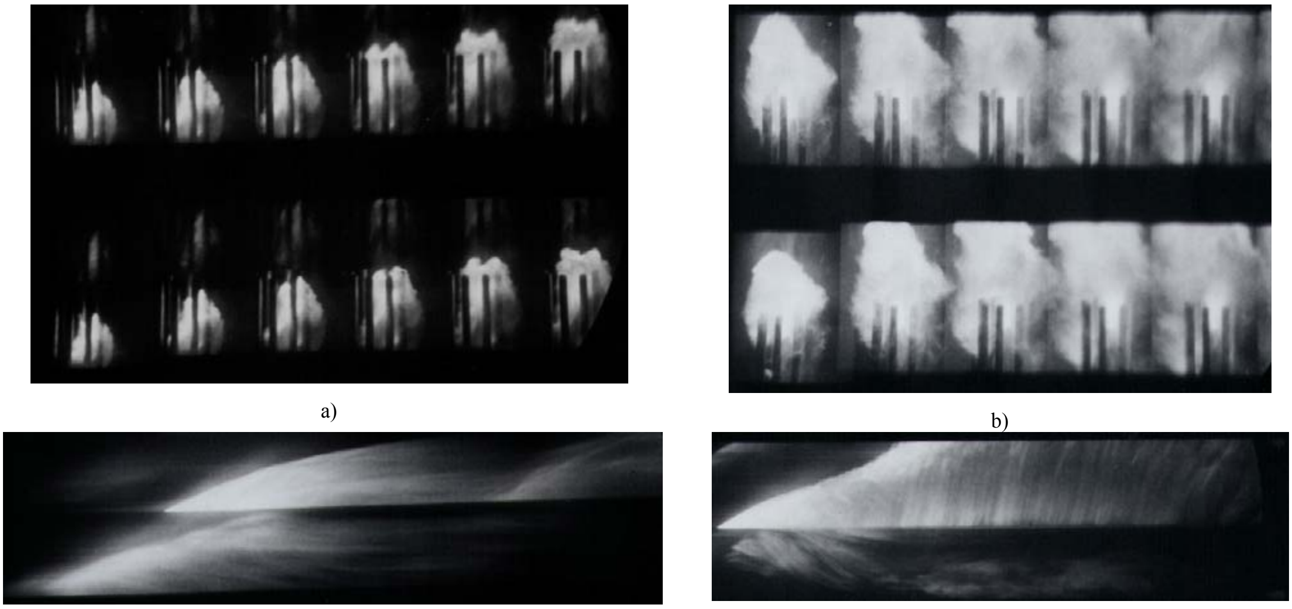
With discharge current increase ( i.e. increase of condensator bank voltage) the plasma compression flow length increases and the diameter in the region of maximum compression decreases in all gases. With a temporal increase of current, the plasma compression flow length increases. Plasma velocity is an increasing function of discharge current. With the temporal decrease of discharge current (compression plasma flow quenching), plasma velocity decreases.

The fourth phase of the MPC operation is the compression plasma flow decay. The compression plasma flow disappears for about 70 $\mu$s in all gases with the discharge current decline. The compression plasma flow quenching is the consequence of condensator bank discharge. If the input energy could be supplied continually, the quasistationary phase would be practically unlimited and the next decay phase would be postponed [1]. In that case the MPC would operate as the stationary plasma source. That is, the continual ionization processes would occur in a working gas which is introduced in the inter-electrode region. The ionized gas (plasma) would be steadily accelerated and permanently compressed.

The obtained MPC current duration was ~140 $\mu$s in all gases (with the capacitor bank energy of 5-10 kJ).

*Deceleration regime*

The MPC discharge development in the deceleration regime in argon and hydrogen at the pressure of 20 000 Pa (Fig.11) was investigated. Later breakdown on the top of the cathode occurs for ~ 30 $\mu$s in argon and ~5 $\mu$s in hydrogen. In argon, the breakdown occurs again (Fig.11c) for about 120 $\mu$s after begining of discharge. It corresponds to the second discharge current half period.



a)

b)

c)

d)

**Figure 11.** MPC discharge development in argon (a,c) and hydrogen (b,d) at the pressure of 20 000 Pa; (a,b) framing records at 2 $\mu$s, starting 20 $\mu$s after the beginning of the discharge; streak records at: c) 2 $\mu$s/mm and d) 1 $\mu$s/mm. Thin white arrow denotes the top of the cathode and thick white arrow denotes the second halfperiod of breakdown current

The shock front velocity in argon is 2 km/s and in hydrogen 4 km/s. The plasma velocity in hydrogen is 40 km/s, but it rapidly decreases with the plasma departure from the top of the cathode, as well as with the discharge current decrease. In argon, the compression plasma flow is not even formed, but with the discharge current decrease a row of parallel fair and dark regions was formed. Those regions are constant in time, i.e. the deceleration regime changes in to regime with periodical structures.

## Conclusion

In this work, the digital image acquisition technique using the Imacon 790 ultra-high-speed camera is presented. The technique is applied to magnetoplasma compressor discharge investigation. Both modes of Imacon recording - framing and streak-were used, beeing complementary in performing complete qualitative and quantitative phenomena analysis. On the basis of records, two MPC working regimes were noticed, depending on working gas pressure. Because of its importance and applicability, special attention was payed to the acceleration-compression regime exising at low pressures [1]. Discharge phases in this regime were identified and their duration was measured. Breakdown points and shock front velocities were determined for three types of working gases at different pressures. The quasi-stationary compression flow phase, as particularly interesting, was studied in details. Time of compression flow forming related to discharge beginning, its duration and dimensions in nitrogen, argon and hydrogen at various pressures were determined from the records. Streak records enabled the plasma velocity measurement in compression flow. Maximum velocity was obtained in hydrogen at the pressure of 1000 Pa. Streak records enabled distinguishing of compression flow microstructures and determination of their frequences. The digital technique record has lower characteristics than a polaroid film [9], what is partially the consequence of video camera quality. Finally, the digital imaging technique can be used as a film substitution for microsecond and nanosecond recordings, regarding abundance of informations which it offers.

## References

[1] MOROZOV,A.I. Principles of Coaxial (Quasi-) Steady-state Plasma Accelerators, *Sov. J. Plasma Phys.* (*Engl. Transl.*), 1990, vol. 6, pp.69-78.

[2] PURIĆ,J., DOJČINOVIĆ,I.P. et. al. Electric and Thermodynamic Properties of Plasma Flows Created by Magnetoplasma Compressor, *Plasma Sources Sci. Technol.*, 2004, 13, p.74-84.

[3] DOJČINOVIĆ,I.P., GEMIŠIĆ,M.R. et al. Investigation of Plasma Parameters in a Magnetoplasma Compressor, *Journal of Applied Spectroscopy*, 2001, 68, pp.824-830.

[4] ANANIN,S.I., ASTASHINSKII,V.M., et. al. Study of the Formation of Plasma Streams in a Quasistationary High-Current Plasma Accelerator, *Sov. J. Plasma Phys.* (*Engl. Transl.*), 1990, vol.16, pp.102-107.

[5] HADLAND PHOTONICS, Imacon principles, Imacon 790-the image converter camera system, Bovingdon, 1984, pp.6-7.

[6] HELD,M. Ballistic Detonics Instrumentation in High Speed Photography, SPIE V.1032 *High speed photography and photonics*, Xian, 1988, pp. 278-293.

[7] JANEV,J. Investigation of Detonics Phenomena Using Ultra High Speed Recording (In Serbian), *Proccedings of XV Symposium on Explosive Materials*, Užice, 1984, pp.231-240.

[8] KEKIĆ,G., DOJČINOVIĆ,I.P. New Recording Technique Using Ultra High Speed Converter Camera Imacon 790 (In Serbian), *Proccedings of XXI Symposium on Explosive Materials*, Tara, 2001, p.603.

[9] KEKIĆ,G., DOJČINOVIĆ,I.P., PURIĆ,J. Digital Imaging Technique Using Ultra High Speed Converter Camera Imacon 790, 1 st *Symposium for Explosive Materials, Weapons and Military Technology*, Ohrid, 2002, p.717.

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# Proučavanja kompresionih tokova plazme korišćenjem ultrabrze kamere IMACON 790

**Prikazani su rezultati tehnike digitalizovanog snimanja ultrabrzom kamerom na ispitivanje pražnjenja u magnetoplazmenom kompresoru. Proučavani su osnovni režimi rada ovog izvora kvazistacionarnih kompresionih tokova plazme na niskim i visokim pritiscima. Analiziran je vremenski razvoj pražnjenja: proboj, formiranje udarnog talasa i kompresionog plazmenog toka, gašenje pražnjenja. Izmereni su osnovni parametri plazme kao što su brzina, dimenzije plazmenog toka, vreme trajanja pojedinih faza pražnjenja. Brzina mikrostruktura kompresionog toka određena je na osnovu snimaka plazme dobijenih "streak" tehnikom u vodoniku, argonu i azotu, na pritiscima 10 – 50000 Pa. Utvrđeno je da su najveće brzine plazme dobijene u vodoniku na pritisku od 1000 Pa i da su one 100 – 120 km/s.**

*Ključne reči*: **ultrabrza kamera, digitalizovano snimanje, merenje brzine, plazma, magnetoplazmeni kompresor.**

# Recherce sur les écoulements compressibles de plasma en utilisant la caméra à grande vitesse IMACON 790

**On a démontré les résultats de l'application de l'enrégistrement digitalisé par une caméra à grande vitesse sur l'investigation de la décharge dans le compresseur magnétique à plasma. On a étudié les principaux régimes de fonctionnement de cette source des écoulements compressibles et quasistationnaires de plasma à basses et hautes pressions. Le dévelopement temporel de la décharge est analysé: projection, création de l'onde de choc et de l'écoulement compressible de plasma et coupage. On a mesuré les paramètres principaux du plasma comme la vitesse, les dimensions de l'écoulement de plasma et la duration des phases de décharge. La vitesse des microstructures dans l'écoulement compressible est déterminée à l'aide des enrégistrements du plasma obtenus par la technique de l'enrégistrement continu ("streak") dans l' hydrogène, l'argone et le nitrogène, sous pressions de 10 à 50000 Pa. Les plus grandes vitesses du plasma (100 – 200 km/s) sont mesurées dans l' hydrogène sous pression de 1000 Pa.**

*Mots-clés*: **caméra à grande vitesse, enrégistrement digitalisé, mesure de la vitesse, plasma, compressur magnétique à plasma.**