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Ing. Jozef Kaiser

# GENERACE A STUDIUM PLASMY PRODUKOVANÉ ABLATIVNÍMI VÝBOJI V KAPILÁRACH

# GENERATION AND STUDY OF HIGH-DENSITY METAL- AND DIELECTRIC- VAPOR PLASMAS PRODUCED BY ABLATIVE CAPILLARY DISCHARGES

Teze doktorské disertační práce

PhD Thesis

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| Obor: | Fyzikální a materiálové inženýrství |
| Školitel: | Prof. RNDr. Miroslav Liška, DrSc.<br>Doc. Sergei V. Kukhlevsky, DSc. |
| Oponenti: | Prof. Ing. Miroslava Vrbová, CSc.<br>RNDr. Pavel Zemánek, Ph.D.<br>Prof. László Kozma |
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# 1. INTRODUCTION

In recent years ablative plasmas generated by capillary discharges received a considerable attention in literature because of their possible application in electrothermal launchers, laser-driven particle accelerators, thin film deposition and soft x-ray lasers.

Depending on the composition of capillary material there are two different types of generated plasmas: dielectric- and metal- vapor plasmas. The parameters of generated plasmas (density, temperature and purity) depend on the parameters of the capillary, electrodes and electrical circuit.

The most widespread methods for study of plasma parameters in capillary discharged plasmas are spectroscopy and interferometry. The plasma is usually studied by investigating spectral lines emitted by metal or dielectric vapor discharge, utilizing emission spectroscopy. Laser Induced Breakdown Spectroscopy can be used for studying plasma homogeneity and purity. Interferometry is useful in diagnostics of plasmas with high densities. All of the above-mentioned methods have limitations and disadvantages. Knowing the limits of how to apply a certain method is crucial for exact determination of parameters of generated plasmas, and for further use of different applications.

Theoretical models of plasmas produced by capillary discharges are describing processes in this type of plasmas by integral balance equation of mass, momentum and energy balance. The flux of mass leaving the capillary by axial motion is replenished by a radial inward flow of matter. Consequently the radial component of the mass flux plays a principal role in the mass and energy balance. Nevertheless, up to now the mechanism of this process has not been explained. Theoretically the radial flux of mass is treated very approximately. The radial motion of plasmas has not been studied experimentally. Our research groups presented the model of “glow-to-arc discharge transition” (based on experimental observation), which shows the principal role of the explosive ablation of the electrode surface in the radial motion of mass and the generation of dielectric vapor plasmas.

# 2. PRESENT STATE

Institutes, which have the most significant results in investigation of plasmas generated by capillary discharges, are:

- University of California, Lawrence Livermore National Laboratory, Livermore, California 94550, USA.
- Plasma Physics Division, Naval Research Laboratory, Washington D.C. 20375, USA.
- Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado 80523 USA.

- Department of Physics, Clarendon Laboratory University of Oxford, Parks Road, Oxford, OXI 3PU, GB.
- Brown Boveri Research Center, CH-5401 Baden, Switzerland.
- Plasma Physics Department, Soreq Nuclear Research Center, Yavne 70600, Israel.

The method LIBS is studied, applied and improved primarily in the following institutes:

- Dave Cremers' group, Los Alamos National Laboratory, California, USA.
- Marchwood Engineering Laboratories, CEGB, Marchwood, Southampton SO4 4ZB, Great Britain.

## 2.1. Generation of metal- and dielectric- vapor plasmas

Production of ablative plasmas by an electrical discharge through a capillary insulator was proposed previously [1]. In this technique a discharge heats the capillary plasma that provides further evaporation of the capillary walls and electrode material. The created plasma is confined by the capillary walls and electrodes (closed-geometry capillaries) [2], or flows into vacuum cell through a hollow electrode [3]. The main disadvantage of the closed-discharge device is the difficulty of controlling plasma parameters. The major advantage of the hollow-electrode design is the separation of plasma creation and its possible heating.

For generation of dielectric plasmas the electrode ablation can be reduced to a few percents of the total ablation by the use of a high thermal-conduction electrode material with a high evaporation temperature [4]. Pure metal-vapor plasmas have been produced in the hollow-electrode-capillary μs-discharge using powdered electrodes [3]. The use of this technique has been largely restricted by the complexity of the powdered-electrode preparation.

The values of the discharge conditions (e.g., current, charging voltage, discharge duration, plasma electron density $N_e$ and temperature $T_e$) are varying widely between experiments. These can range from currents of $10^{-6}$ A to $10^{-1}$ A in dc glow capillary discharges with $N_e \leq 10^9$ cm$^{-3}$ and $T_e \leq 5$ eV, to currents and charging voltages of tens to hundreds of kA and kV, respectively in transient (*ns* to *μs* time scale) capillary discharges with $N_e \geq 10^{22}$ cm$^{-3}$ and $T_e \leq 1$ eV (see for example [5] and references therein).

## 2.2. Diagnostic of plasmas

Characterization of plasmas parameters can be carried out by several different methods [6]. They involve diagnostic methods like measurements of the capillary-discharge electric-circuit parameters [7], investigation of plasma density, temperature and purity by spectroscopic methods [5, 8], as well as interferometric measurements [9, 10].

Plasma diagnostic studies generally focus on spectroscopic methods, mostly on time-resolved emission spectroscopy – i.e. time-resolved observation of Stark line broadening of spectral lines emitted from capillary or electrode materials. In the region of $10^{16}$ $-10^{18}$ cm$^{-3}$ electron density is usually measured by this method [5]. For higher densities, the strong broadening of lines along with the high spectroscopic background makes using this technique problematic [11]. Stark spectroscopy is utilized also for study of plasma temperature and purity [5, 8]. The technique of Laser Induced Breakdown Spectroscopy (LIBS) [12, 13] utilizes the high power densities obtained by focusing the radiation from a pulsed, fixed frequency laser to generate a luminous micro-plasma from solid, liquid or gaseous samples in the focal region. The plasma composition is representative of sample composition. In order to exploit LIBS for analytical purposes, extensive studies have been carried out to determine electron density, temperature and line shapes and their validity of analytical outcomes (see for example [13] and references therein).

Application of interferometry has been carried out [9] for study of dense plasmas, in which case application of spectroscopic methods is very difficult. Interferometry can be used also for study of plasma uniformity.

## 2.3. Theoretical models of physical processes in capillary discharges

Several theoretical models analyze the conditions in the ablative capillary (see for example [14-19] and references therein). In the initial works Ogurstova *et al.* [14] and Rozanov [15] recognized that capillary discharges from a capillary with ablative walls are controlled by axial flow of ablated wall material. In Niemeyers model described in work [16] an evaporation-dominated arc consists of three components: arc zone inside the channel, vapor layer and plasma jet. The arc/vapor balance is described by the integral balance equation of mass, momentum and energy. The model in [16] was further developed in work [17] in order to quantify the phenomena of flow blocking and reverse flow heating. The radiative energy transport in these works is characterized by a nondimensional transparency factor $\vartheta$ [16] relating the power flux towards the wall to the arc power. No $\vartheta$ values are available for ablation controlled [17] arcs. In the works of Zoler and Cuperman [18] and Cuperman *et al.* [19] quasi one-dimensional non-ideal fluid equations describing the steady state plasma flow are presented.

On the basis of the models above, the ablation of electrode material contributes a negligible amount of metal to the plasma. However, it has been found experimentally [20, 21] that the weight of metal ablated from electrodes can be about the same as the weight of ablated dielectric.

Theoretical models that describe compression of plasma column (so called pinch), necessary for intense tabletop x-ray sources, based on magneto- hydrodynamic (MHD) equations are presented in [22, 23].

# 3. AIMS OF THE DISSERTATION

The aims of the dissertation can be separated into two major parts:

- **Experimental part** - development of plasma-generating and diagnostic methods for high-density capillary plasmas.
- **Theoretical part** – presenting “surface explosion theory” with principal role of the explosive ablation of the electrode surface; theoretical study of the *Z*-pinch compression of plasma using simplified MHD model.

# 4. MAIN RESULTS

The main goal of our work was to construct and optimize an experimental apparatus for metal- and dielectric- vapor production, to produce a plasma with requested parameters and to apply the different plasma diagnostic methods and techniques; as well as to apply and improve the recent theoretical models.

## 4.1. The metal- and dielectric- vapor generator

A generator able to produce both metal- and dielectric- vapor was constructed. It was further optimized to be able to provide various plasma diagnostic measurements, together with the different diagnostic parts of the set-up. Several types of capillary material (Teflon-$(CF_2)_n$, $(H_2C0)_n$, $SiO_2$, $Al_2O_3$, BeO) and electrodes (Al, Fe, Cu) were used. The most important measurements carried out with the generator-detector system were:

- time-resolved spectroscopic measurements of plasma parameters inside the generator (between two electrodes)
- time-resolved spectroscopic measurements of plasma-jet (escaping from the hollow electrode)
- time-resolved interferometric measurements of plasma-jet.

Using this set-up, pure, high-density metal-vapor plasma was produced utilizing a μs-discharge through a short (*4* mm) BeO capillary [21]. The capillary ablation was less than *1* % of the total ablation [21].

Pure, dielectric vapor was produced under similar experimental conditions, using a Teflon-$(CF_2)_n$ capillary instead of a BeO capillary. The density of dielectric vapor reached $N_{VAP} > 10^{19}$ cm$^{-3}$ [24].

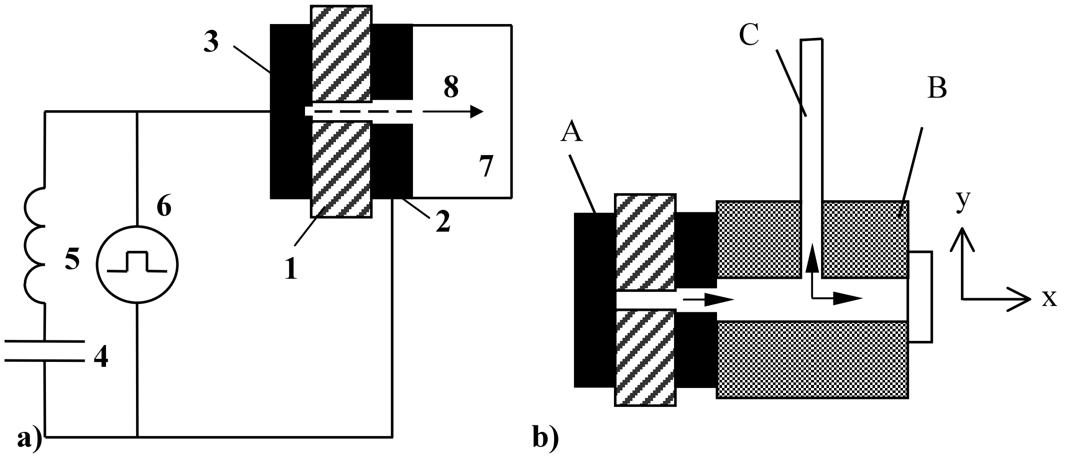

*Figure 1. a) A schematic diagram of the experimental setup for the plasma generation 1 – capillary, 2 – anode, 3 – cathode, 4 – capacitor, 5 – inductance, 6 – H.V. pulsed generator, 7 – vacuum chamber, 8 – plasma flow. b) Metal or dielectric vapor generator with diffusion capture A – generator, B – diffusion capture and C – channel for metallic vapor.*

## 4.2. Diagnostics of plasmas produced by capillary discharges

As it was already mentioned, the exact knowledge of plasma parameters is important for different applications. Diagnostic of the generated plasma was carried out by a number of diagnostic methods. They involved among others:

- measurements of the capillary discharge electric circuit parameters,
- time-resolved spectroscopic measurements of plasma parameters,
- investigation of plasma purity utilizing LIBS,
- interferometric measurements of plasma-jet.

### *4.2.1. Measurements of the electric circuit parameters*

In order to understand the physical mechanism involved in the mass motion and the related ablation produced effects, the dependence of plasma resistivity, temperature and density on discharge voltage was studied experimentally. For the experimental conditions reported in [24] more than *90* % of the power is dissipated in the first half period of the discharge, plasma density is proportional to voltage, and there is no significant change in plasma resistivity and temperature for different discharge voltages.

### *4.2.2. Spectroscopic measurements*

Time-resolved spectroscopic measurements of plasmas produced by capillary discharge were applied mainly to investigate plasma density and temperature.

The application limits of this method were also considered. The utilized system for spectral analysis enabled temporal resolution *40* ns – *10* ms and has a spectral resolution of, typically *0.03* nm. We studied:

- temporal behavior of plasma composition by observing the emission lines of the neutral atoms and single ionized ions of Fe, Be and O and calculated the metal vapor density and electron temperature,
- the plasma density and temperature for dielectric-vapor plasmas produced by capillary discharge,
- the application limits of the spectroscopy method in the case of plasmas produced by pulsed discharge through Teflon-$(CF_2)_n$ capillary.

It was shown that by using capillary discharges pure metal vapor plasmas can be produced with electron temperature ~ *0.5* eV and peak electron densities above ~ $10^{19}$ $cm^{-3}$ [21]. It can be expected on the basis of these measurements that a further developed device for soft x-ray capillary laser will be applied.

Plasma electron density and electron temperature with the peak values above $10^{17}$ $cm^{-3}$ and ~ *0.8* eV, respectively, were corroborated from spectroscopic measurements of dielectric-vapor plasmas [11, 24].

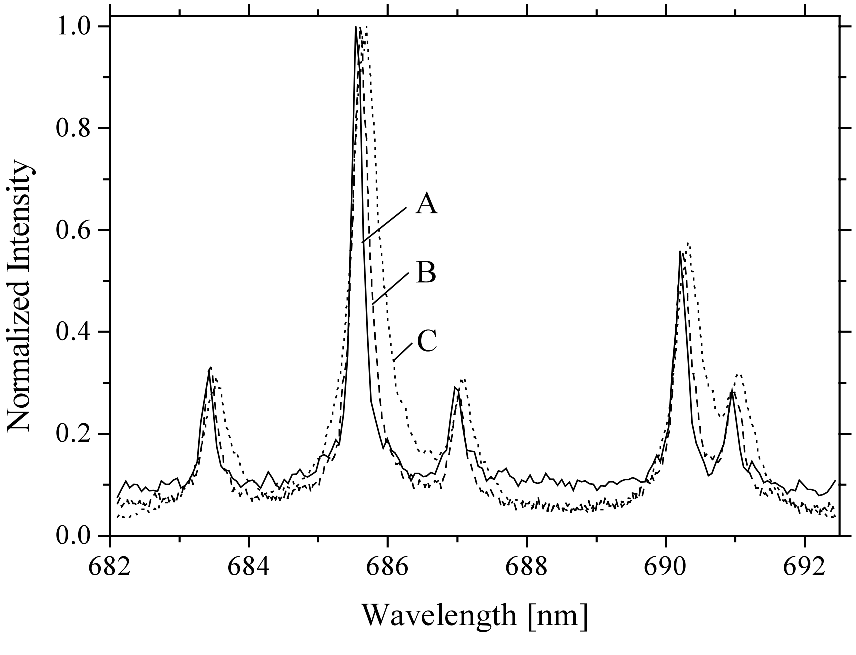

*Figure 2. Time-resolved plasma spectra for the different discharge energy densities A – 10 J $cm^{-3}$, B – 20 J $cm^{-3}$, and C – 30 J $cm^{-3}$. The spectra were measured at the time of peak discharge current (Fig. 2. from [11] p. 1091).*

The peak electron density in the ablative, dense plasma produced by the pulsed discharge through a Teflon-$(CF_2)_n$ capillary has been measured using Stark spectroscopy of the atom emission lines in the range of electron density $10^{16} – 10^{18}$ cm$^{-3}$. The time-resolved profiles of several F(I) lines were detected for the different discharge energy densities and compared with theoretical data. The result show [11] that the method can be used for the diagnostics of plasmas with peak electron density up to about $3$ x $10^{7}$ cm$^{-3}$, which corresponds to a discharge energy density of $9$ kJ cm$^{-3}$.

Laser Induced Breakdown Spectroscopy was utilized to study plasma purity. This method was based on the measurements of the laser-induced spectra from the metal vapors condensed on the capillary wall [20]. The high purity of generated metal-vapor plasma was shown. Furthermore the diagnostic technique LIBS was studied, improved and applied for the analysis of a wide range of different solid and liquid samples [13, 25-27].

### *4.2.3. Interferometric measurements*

For interferometric measurements the interferometer was applied in Mach-Zehnder arrangement. The set-up was optimized for time-resolved interferometric measurements. The estimated vapor peek electron density from these measurements was ~ $10^{17}$ cm$^{-3}$.

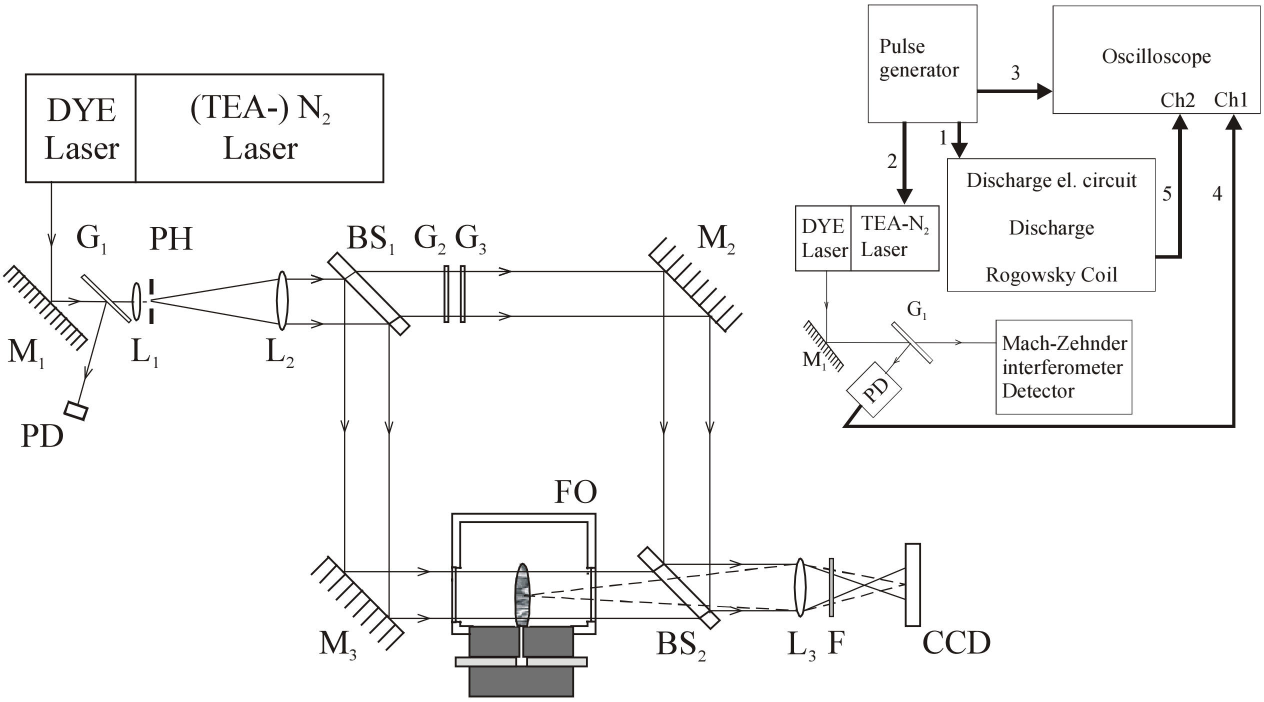

*Figure 3. Experimental set-up for interferometric measurements together with the set-up for timing of the laser pulse with respect to the onset of the discharge current. $M_1$, $M_2$, $M_3$ – mirrors; $G_1$, $G_2$, $G_3$ – quartz plates; $L_1$, $L_2$, $L_3$ – lenses; PD – photodiode; PH – pin hole ($\phi$ 25 $\mu$m); $BS_1$, $BS_2$ – beam splitters, FO – phase object, F – filter and CCD – detector. 1 – Discharge trigger pulse, 2 – Laser trigger pulse, 3 – Oscilloscope trigger pulse, 4 – Signal derived from Rogowsky coil, 5 – Photodiode signal.*

## 4.3. Theoretical models of physical processes in plasmas produced by capillary discharge

### *4.3.1. The model of "glow-to-arc discharge transition"*

It was found experimentally that the weight of metal ablated from electrode surfaces in capillary discharges could be about the same as the weight of ablated dielectric. However, the role of impacting metal particles into the capillary wall is not considered in the recent models.

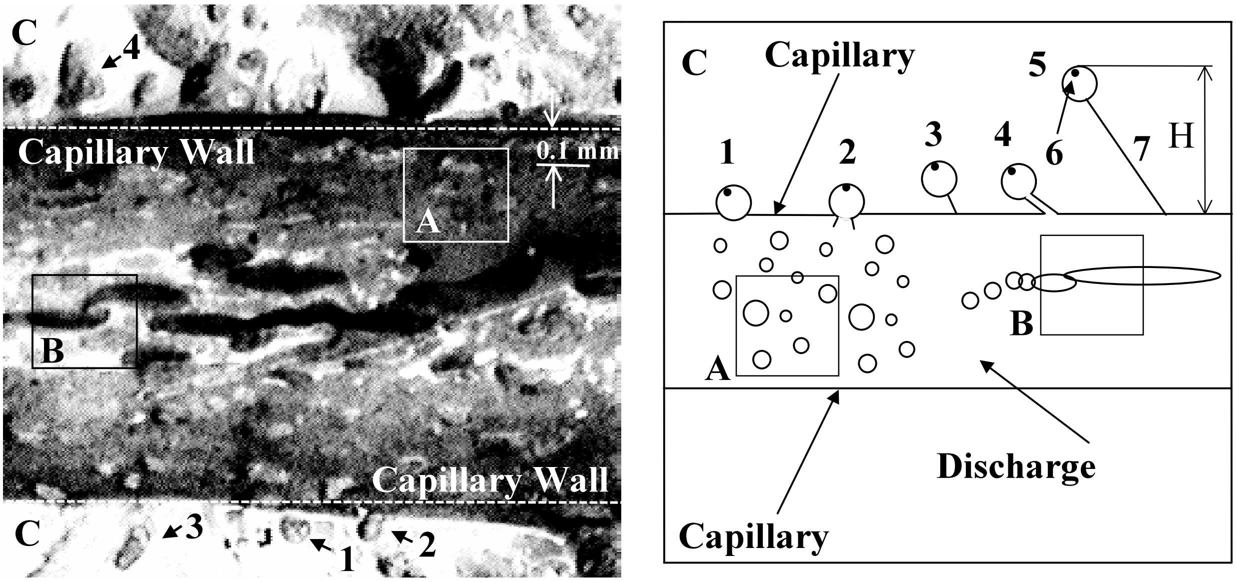

*Figure 4. Photograph of the discharge channel wall (the capillary cross section) after a few discharges, together with the schematic cross section of the capillary. (1-5) - micro-bubbles filled with dielectric vapors, 6 - the metallic particle, 7 - the particle-produced channel, H - the particle penetration depth, A - the bubbles on the discharge channel surface, B - the slit produced by the row of bubbles and C - capillary wall (Fig. 4. from [24] p. 340).*

Our model of "glow-to-arc discharge transition" with explosive electrode processes (also called "surface explosion theory") takes also this fact into account. The model [24] is based on the following main points:

- In the cathode and anode regions the electric field strengths ($E_C$ and $E_A$ (V/m)) are $10^2$ - $10^3$ times higher than that in the plasma-column region.
- In the case $E_{C,A}$ reaches a critical value, the micro-defects on the electrode surface are exploded and the particles move with hyper velocities ($u_p \sim 10^5$ cm/s) in the radial direction to the capillary wall.
- The high velocity and temperature of the metallic particles causes that they penetrate into the radiation-heated wall and evaporate the dielectric material.

- Part of the evaporated wall material gets directly into the plasma column; another part produces micro-bubbles filled with dielectric vapors.
- After the pressure in the bubble reaches a critical value the bubble opens and the vapors move radially to the discharge axis with high velocity.
- The vapor density is mainly determined by the erosion rate of electrodes, which is a function of current and electrode material.

We should note in connection with this model that further investigation of the crater formation, crater diameter and perforation hole diameter, as well as the mechanism of ablation and its effect on plasma formation is needed.

### *4.3.2. Capillary z-pinch model*

In the capillary discharges devoted to soft x-ray production, an efficient compression of the plasma column (so called pinch) is needed to create hot and highly ionized plasma. To describe the pinch dynamic, we prepared a model based on a simplified version of the Braginsky-type [28, 29] magneto- hydrodynamics code. For simplicity, the model assumes that initially the plasma is uniformly ionized so that the current density is uniformly distributed inside the column.

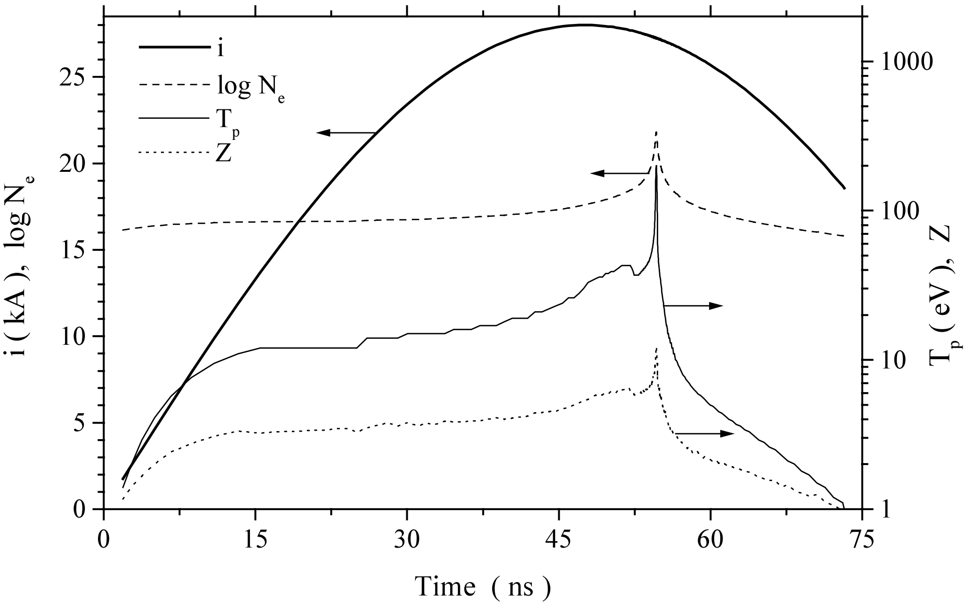

*Figure 5. Calculated time behaviors of current i, plasma electron density Ne ($cm^{-3}$), plasma temperature T and the main stage of ionization Z for a discharge with parameters: peak current $i_{peak}$ ~ 30 kA, half cycle duration T/2 ~ 90 ns, and initial pressure of argon $p_{Ar}$ = 46.66 Pa ( 0.35 torr). The capillary consisted of an ceramic ($Al_2O_3$) channel having diameter $\phi_{cap}$ = 5 mm and length $l_{cap}$ = 14.5 cm.*

The densities of electrons and ions are also assumed to be uniform. In this case the velocity of plasma compression is determined by the speed of external sheet of plasma, while inside the column the velocity of particles is proportional to the radius. In the model the same balance equation is used for both electrons and ions that are considered to be in thermodynamic equilibrium. It takes into account radiative energy losses, plasma viscosity and ionization processes. The model predictions were compared with our experimental results and with measurements described in Ref [30]. We found that in spite of the simplicity of our model it properly accounts for the scaling of the implosion features with variation of the initial gas pressure and current pulse shape, and provides a valuable guidance for experimental optimization. The use of this model for theoretic predictions of conditions in "metal-vapor z-pinch" can be expected.

# 5. CONCLUSION

Ablative plasmas produced by capillary discharge have recently received great attention. This could be due to the possible application (soft x-ray laser microscopy and lithography), as well as to the interest in studying the physical phenomena (fusion research, intense sources of continuum and line emission). The plasma generator based on capillary discharge constructed in our laboratory, which is able to produce both metal- and dielectric- vapor, was optimized to provide various plasma measurements. It can be expected that further developed device for soft x-ray capillary laser will be applied.

The most widespread methods for study of plasma parameters in capillary discharged plasmas are spectroscopy and interferometry. The plasma is usually studied utilizing emission spectroscopy for investigating spectral lines emitted by metal or dielectric vapor discharge. Laser Induced Breakdown Spectroscopy can be used for studying plasma homogeneity and purity. Interferometry is useful in diagnostics of plasmas with high densities. All of the above-mentioned methods have limitations and disadvantages. Knowing the limits of how to apply a certain method is crucial for exact determination of parameters of generated plasmas, and its further use of different applications. Temporal behaviors of metal- and dielectric-vapor plasma composition and parameters by observing emission lines of atoms and single ionized ions of different elements, together with applications limits of this method were studied. LIBS was utilized for plasma purity-measurements. Time-resolved interferometric methods were also conducted.

Theoretical models of plasmas produced by capillary discharges are describing processes in this type of plasmas by integral balance equation of mass, momentum and energy balance. The flux of mass leaving the capillary by axial motion is replenished by a radial inward flow of matter. Consequently the radial component of the mass flux plays a principal role in the mass and energy balance. Nevertheless, up to now the mechanism of this process has not been explained. Theoretically the radial flux of mass is treated very approximately. The radial motion of plasmas has not been studied experimentally. Our research groups presented the model of "glow-to-arc discharge transition" (also called "surface explosion theory"), which shows the principal role of the explosive ablation of the electrode surface in the radial motion of mass and the generation of dielectric vapor plasmas.

An analysis of argon filled capillary z-pinch discharge is also presented. This type of pinch is generally used in the capillary soft x-ray lasers. A theoretical study of the z-pinch compression of the plasma was conducted by developing a simplified MHD model, which takes into account the effect of an external circuit. The effect of the circuit parameters and of the initial capillary conditions on the plasma evolution was examined, and the performance of the code was verified comparing the theoretical predictions with the experimental measurements. The model provides a valuable guidance to the experimental optimization.

Most of our results in the field of plasma generating, diagnostic and improving of diagnostic methods has already been published (see for example [11, 21, 24-27]. Utilizing of above mentioned methods for plasma generation and study was successfully conducted in our research laboratories (at the Institute of Mechanical Engineering, Technical University of Brno, Czech Republic; at Faculty of Physics, University of Pécs, Hungary and at Faculty of Physics, University of L’Aquila, L’Aquila, Italy).

# 6. SHRNUTÍ

V současné době plasma produkovaná ablativním kapilárním výbojem získává velkou pozornost. Je to dáno možnými aplikacemi (mikroskopie a litografie pomocí laserů, vyzařujících v měkké rentgenové oblasti), ale také nutností hlubšího studia fyzikálních jevů (termonukleární reakce, intenzivní zdroje emise spojitého a čárového spektra). Fyzikální popis generace, zkoumání a aplikace plasmy z kapilárních výbojů je velmi komplikovaný a zahrnuje množství experimentálních problémů (délka výboje pro generaci plasmy je řádově µs nebo ns, je zapotřebí generovat plasmu spektrálně čistou o vysoké hustotě, homogenní a malého průměru o délce ~ *20* cm atd.). V současné době je popsána sestava pouze jednoho funkčního laserového zesilovače, vyzařujícího na vlnové délce *46,9* nm realizovaná J.J.Roccem et al. v 1996. K dosažení laserového záření pod *46* nm se může využívat excitace vyšších Z-iontů. Prvky blízké neonové sekvenci jsou kovy, které mají pevné skupenství při pokojové teplotě.

Nejpoužívanější metody ke zkoumání charakteristik kapilárních výbojů jsou spektroskopie a interferometrie. Plasma je většinou zkoumána pomocí emisní spektroskopie; vyšetřují se spektrální čáry emitované z plasmy kapilárního výboje. Laserová spektroskopie (LIBS) může být využita ke studiu homogenity a čistoty plasmy. Interferometrie je užitečná k výzkumu plasmy s vysokou hustotou. Každá ze zmíněných metod má své omezení a nedostatky. Znalost omezení a použitelnosti jednotlivých metod je rozhodující k exaktnímu určení parametrů generované plasmy a k jejímu použití.

Teoretické modely popisují ablativní kapilární výboje pomocí zákona zachování hmotnosti, hybnosti a energie. Axiální tok hmoty z kapiláry je vyrovnán radiálním tokem hmoty ze stěn kapiláry a z elektrod. Z toho vyplývá, že radiální složka toku hmoty má hlavní roli v zákonu zachování energie a hmotnosti. Avšak, zatím přesný mechanismus radiálního toku nebyl popsán. V teoretických modelech je radiální tok hmoty stanoven pomocí experimentálně získaných koeficientů.

Hlavním přínosem disertační práce je vyložení původního postupu pro generaci vysokočistotní metal-vapor a dielektrické plasmy. Tento druh plasmy je vyžadována pro použití v aplikacích výše uvedených. Je uveden postup konstrukce a optimalizace přístroje pro generaci kapilárních výbojů požadovaných parametrů. Tento přístroj umožňuje rovněž aplikaci zmíněných diagnostických metod ke studiu plasmy.

V práci je popsáno použití jednotlivých diagnostických metod pro zkoumání plasmy, mj.:

- zjišťování elektrických parametrů výboje (studium časově rozlišených V-A charakteristik a energetické poměry výboje),
- časově rozlišená emisní spektroskopie, (byla použita na zkoumání složení a parametrů plasmy včetně stanovení hranice použitelnosti této metody),
- laserové spektroskopie (zkoumání homogenity plasmy),
- časově rozlišená interferometrie.

V teoretické části je představena „Teorie exploze povrchu“, která popisuje roli explozivních ablací povrchu elektrod v radiálním pohybu hmoty a generaci dielektrické páry uvnitř kapiláry a vliv tohoto jevu na teplotu a hustotu plasmy.

Dále je uveden teoretický popis komprese plasmy v přítomnosti silného elektromagnetického pole (tzv. z-pinch) pomocí zjednodušeného magneto-hydrodynamického (MHD) modelu. Tohoto fenoménu se využívá ke generaci záření v měkké rentgenové oblasti pomocí kapilárních výbojů. Uvedeným modelem byla zkoumána vliv změn parametrů externího elektrického obvodu a počátečních podmínek v kapiláře na generovanou plasmu. Výsledky modelových výpočtů byly srovnány s naměřenými hodnotami společně s hodnotami získanými z komplexnějších modelů.

Část našich výsledků v oblasti generace, diagnostiky a vylepšení diagnostických metod již byla uveřejněna v publikacích [11, 21, 24-27]. Diagnostika plasmy pomocí metod časově rozlišené emisní spektroskopie, laserová spektroskopie – LIBS a interferometrie společně s vypracováním modifikované teorie kapilárních výbojů byly provedeny nebo se provádí v našich výzkumných laboratořích (v Ústavu fyzikálního inženýrství, Vysokého učení technického v Brně, na Fakultě fyziky University Januse Pannoniuse, v Pécsi a na Fakultě fyziky University L’Aquila, v L’Aquila).

# 7. ZUSAMMENFASSUNG

Das Studium der Literatur zeigt, daß durch Kapillar-Entladung (capillary discharge) erzeugte abtragende Plasmen (ablative plasmas) in letzter Zeit große Aufmerksamkeit erzielen. Das kann einerseits auf die möglichen Anwendungen (Mikroskopie und Lithographie mit weicher Röntgenstrahlung (soft x-ray microscopy and lithography)) als auch andererseits auf die Untersuchung physikalischer Phänomene (Fusionsforschung, intensive Quellen kontinuierlicher und Linien Emission) zurückgeführt werden. Da die Erzeugung, Untersuchung und Anwendung von capillary discharged plasmas kompliziert ist und eine Fülle von experiementellen Problemen mit sich bringt (es handelt sich um Plasmen mit einer Lebensdauer im µs bis ns Bereich, und z.B. erfordert die Erzeugung von auf Kapillar-Entladung basierenden Quellen weicher Röntgenstrahlung hohe Dichte und Reinheit, kleine Durchmesser und ungefähre 20 cm lange Plasmaröhren), gelang es bis jetzt nur J.J.Rocca et al., 1996, einen funktionstüchtigen table-top entladungsgepumpten soft x-ray Verstärker bei einer Laserwellenlänge von 46 nm zu realisieren. Um Laserwellenlängen unterhalb von 46 nm in der Ne-artigen isoelektrischen Sequenz zu erhalten, sollte die Anregung höherer Z-Ionen genutzt werden. Die Elemente der Ne-artigen Sequenz sind feste Metalle bei Raumtemperatur.

Die am weitesten verbreitete Methode zur Untersuchung der Plasma Parameter in capillary discharged plasmas sind Spektroskopie und Interferometrie. Das Plasma wird normalerweise mit Emissions-Spektroskpie untersucht wobei die Spektrallinien, die bei der Gasentladung von Metallen und Dielektrika emittiert werden, bestimmt werden. Mit Induced Breakdown (Induzierter Durchbruch) Spectrokopie kann die Homogenität und die Reinheit des Plasmas untersucht werden. Interferometrie wird bei Plasmen mit hoher Dichte angewandt. Alle hier angeführten Methoden habe Beschränkungen und Nachteile. Die genaue Kenntnis des Bereiches der Anwendbarkeit der einzelnen Methoden ist essentiel für die exakte Bestimmung der Parameter des erzeugten Plasmas, und seine weitere Nutzung in unterschiedlichen Anwendungen.

Theoretische Modelle von durch Kapillar-Entladung erzeugten Plasmen beschreiben die Prozesse in dieser Art des Plasmas durch integrale Gleichgewichtsgleichungen der Masse, der Momente und des Energiegleichgewichts. Der die Kapillare durch axiale Bewegung verlassende Massefluß wird durch den radialen Einfluß von Material wieder aufgefüllt. Somit spielt die radiale Komponente des Masseflusses eine wichtige Rolle im Masse- und Energiegleichgewicht. Trotzdem wurde bis jetzt der Mechanismus dieses Prozesses nicht erklärt. Theoretisch wird der radiale Fluß nur sehr ungenau behandelt. Experimentell wurde die radiale Bewegung von Plasmen noch nicht untersucht. Unsere Forschungsgruppe stellte die „Surface-Explosion Theory“ („Oberflächen Explosions Theorie“) vor, die die essentielle Rolle der explosiven Abtragung

(Ablation) an der Elektrodenoberfläche für die radiale Massenbewegung und die Erzeugung dielektrischer Gasplasmen aufzeigt.

Eine Untersuchung von Ar filled capillary z-pinch discharge wird ebenso präsentiert. Diese Art pinch wird im Allgemeinen in capillary soft x-Ray Lasern verwendet. In Begleitung einer theoretische Untersuchung der z-pinch Kompression des Plasmas wurde eine vereinfachtes MHD Modell entwickelt, das den Effekt eines externen Kreises (circuit) berücksichtigt. Der Effekt des Kreisparameters und der Einfluß der Anfagsbedingungen der Kapillare auf die Entwicklung des Plasmas wurde untersucht, und die Performance des Codes wurde durch den Vergleich der theoretischen Vorhersagen mit den experimentellen Ergebnissen überprüft. Das Modell liefert wertvolle Richtlinien für die Optimierung des Experiments.

Teile unsere Ergebnisse im Bereich der Plasmaerzeugung, Diagnose und Verbesserung diagnostischer Methoden wurden schon veröffentlicht [11, 21, 24-27]. Plasmadiagnose mit zeitaufgelöster Emissionsspektroskopie, LIBS und Interferometrie wurde in unseren Instituten erfolgreich durchgefführt (Institut für Mechanik, Technische Universität Brünn, Tschechien; Institut für Physik, Universität von Pécs, Ungarn, und Institut für Physik, Universität von L’Aquila, Italien).

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# CURRICULUM VITAE

Jozef Kaiser (born 1974) obtained his academic degree Ing. (MSc.) in Physical Engineering from Technical University of Brno, Faculty of Mechanical Engineering, Institute of Physical Engineering, Brno, Czech Republic in 1997. From 1997 he has been a PhD student of the Institute of Physical Engineering under the supervision of Prof. RnDr. Miroslav Liška, DrSc. (University of Technology, Brno) and from 1998 also under supervision of Doc. Sergei V. Kukhlevsky, DSc. (University of Pécs). His theoretical and experimental work concentrated on the field of plasma physics. During his study he established cooperation with Faculty of Physics, University of Pécs, Hungary and Faculty of Physics, University of L'Aquila, L'Aquila, Italy, where he conducted the main part of his experimental work. During the PhD study he participated in 8 research grants. He is co-author in 16 publications.