Bulg. J. Phys. **40** (2013) 85–92

Development, Highlights, and Prospects of Plasma Physics Research in Bulgaria*

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Abstract. In this paper, I offer a brief review of the development of plasma physics research in Bulgaria over the past two–three decades. The main focus is on the highlights of various research groups or individuals alongside their cooperation with leading European universities and institutions in studying laboratory, thermonuclear and astrophysical plasmas.

PACS codes: 01.10.Fv, 95.30.Qd

1 Introduction

Plasma physics aroused out as a relatively independent branch of physical sciences before more than a half of century in connection with the thermonuclear fusion, resolving a number of key problems in astrophysics (for instance, the mechanism of solar coronal heating, solar dynamo, predicting solar cycles periodicity) as well as the elaboration of plasma technologies in a widest aspect: plasma processing and thin film deposition, plasma-based lighting systems, plasma chemistry, plasma spray and bulk materials work, environmental and health applications, one-atmosphere plasma systems, materials synthesis, switches, relays, focus, antennas, power systems, thrusters, generation of high-power coherent electromagnetic waves in the gigahertz/terahertz region, etc.

Large part of aforementioned problems was/is object of examination of bigger and smaller groups of scientists/scholars at institutes of the Bulgarian Academy of Sciences (BAS) and the Faculty of Physics, University of Sofia. Here, we will consider the plasma and gas-discharge physics' topics of the individual research groups pointing out those achievements that found a wide response among the international plasma physics community.

Plasma physics research in Bulgaria received a significant incitement over 70s and 80s of the 20th century when a number of young scientists and students from institutes of BAS and the University acquired scientific degrees in plasma and gas-discharge physics from leading institutions and universities at Moscow and

*Talk at the Second Bulgarian National Congress in Physics, Sofia, September 2013.

Leningrad/Saint Petersburg, Russia. That generation in turn contributed to the emergence of de facto two new generations of plasma physicists in the country.

2 Review of Distinctive Contributions to Plasma Physics in Bulgaria

2.1 Low-temperature gas-discharge plasmas

The most widely studied (with a view of their applications) are the gas discharges: direct current, arc, radio frequency and microwave ones. The study of hollow-cathode discharges is traditionally a trademark of the scientists at the Institute of Solid State Physics (ISSP) of BAS – the investigations have been focused on the use of these discharges as light sources, active laser medium, for depth profile analysis of new materials (R. Djulgerova, V. Mihailov, P. Pramatarov, M. Stefanova); development of coherent (D. Zhechev) and optogalvanic spectroscopy in hollow cathode discharges as an alternative of the classical optical spectroscopy (R. Djulgerova, V. Mihailov, D. Zhechev). There has been worked out fluid (on using the PLASIMO-MD2D platform at Eindhoven University of Technology) and kinetic (with Monte Carlo simulations) models of the hollow cathode discharge (M. Grozeva, D. Mihailova, S. Karatodorov) allowing determination of ions energy, as well as the bulk distributions of various processes involving the plasma electrons. N. Vuchkov, K. Temelkov, and S. Slaveeva at the Laboratory of Metal Vapor Lasers theoretically determined the basic plasma parameters of nanosecond pulsed discharge, typical for laser excitation, notably the radial distributions of gas and electron temperatures. There has been estimated the thermal conductivity of binary gas mixtures, experimentally and theoretically are found the cross sections and rate constants for Penning ionization and non-symmetrical charge-exchange processes in the discharge plasma. The results are published in 20 papers in recognized international journals. Determination of atomic constants such as radiation lifetimes of excites ions and ion states, cross-sections of atom–atom and atom–electron elementary processes of interaction in Cu, Zn, Ti, V, Sc, He (K. Blagoev, G. Malcheva, E. Dimova) is directly connected with plasma physics and atomic spectroscopy. P. Pramatarov and M. Stefanova use the plasma electron spectroscopy for analysis of gas mixtures, based on the registration of secondary electrons arising at Penning ionization of the gas-phase excited-state atoms with metastable gas and metal mixtures. Over the past years K. Blagoev, M. Grozeva, G. Malcheva, and P. Zahariev set up equipments for elemental analysis based on an examination of the intensities of spectral lines emitted from laser-induced plasma. There were carried out investigations of the elemental composition of archaeological ceramics, silver, bronze, gold from various excavations in Bulgaria.

The physics of microwave discharges sustained by travelling electromagnetic waves is a topic of research of my Plasma Physics Group (1980–2005) at the

Faculty of Physics, University of Sofia for more than two decades. The main objective is to create a self-consisting model describing and predicting the discharge structure in a gas and the morphology of the electromagnetic wave sustaining the discharge. The creation of such a model goes through three stages: from 1982 to 1995 E. Mateev, V. Atanassov, E. Benova, I. Ghanashev, P. Staikov, M. Djourelova, and I. Zhelyazkov in 14 papers published in peer-reviewed international journals had offered so called electrodynamic model, including diverse discharges configurations (dielectric tube, metal screen), axially-symmetric and dipole modes of the wave and also the presence of an axial external constant magnetic field. Recall that in magnetic field the ionized medium becomes gyrotropic and while in the isotropic case (plasma without external magnetic field) the travelling electromagnetic wave is a pure surface mode, in magnetized plasma the wave has a complex structure and can be considered as a generalized surface wave. Based on these results V. Atanassov and E. Benova got their PhD degrees in Physics, and I. Zhelyazkov his Doctor of Science in Physics degree. During the second stage (1996–2005) there had been created kinetic collisional radiative models of argon microwave plasma at low and moderate pressures (E. Benova, A. Blagoev, Ts. Petrova, G. Petov, Z. Neïchev, A. Achanova, I. Zhelyazkov, F. M. Dias, C. M. Ferreira, V. Guerra, J. Loureiro). The combined electrodynamic and kinetic model of argon microwave plasma detailed in the PhD thesis of Ts. Petrova (under the supervision of E. Benova) is in a very good agreement with the experimental data in a wide range of pressures. The third stage (from 2006 onwards) is associated with the study of microwave plasma at atmospheric pressure as the theoretical and experimental investigations are carried out by a renewed composition of the Plasma Physics Group (E. Yordanova, M. Atanasova, P. Marinova, Z. Neïchev, T. Bogdanov, V. Marchev, K. Ivanov, A. Blagoev, I. Zhelyazkov), now led by E. Benova. The recent PhD thesis (2013) of M. Atanasova contains a full kinetic and electrodynamic model of surface-wave argon plasma at atmospheric pressure. Recently, interest in this type of discharges is extremely high in view of their applications in biology and medicine. Elaboration and modelling of microwave plasma sources at atmospheric pressure with power of 10–20 W for constructing plasma antennas (and other applications) are also performed by the scientific group of Zh. Kiss'ovski at the Faculty of Physics, University of Sofia, consisting of three PhD students and a few post-graduate students.

It is not surprising that studies of microwave discharges in magnetic field have points in common with developed by S. T. Ivanov (Faculty of Physics, University of Sofia) theory of electromagnetic waves propagation in spatially bounded static and flowing plasma – wide range of geometries of the waveguide structures and dispersion characteristics of propagating therein electromagnetic waves that may be used in a study of the ability to generate coherent electromagnetic radiation by an electron beam are contained in a number of publications in prestigious journals, including his dissertation for Doctor of Science in Physics degree.

Physics of high-frequency discharges sustained by travelling electromagnetic waves (of surface-wave type and Travelpiece–Gould mode) have been intensively studied theoretically and experimentally in 1994 onwards by the Plasma and Gas-discharge Physics Group at the Faculty of Physics, University of Sofia led by A. Shivarova – arguably the largest and most productive plasma physics group in Bulgaria – formed in 1987 it consists of 10–12 researchers. Research conducted in collaboration with H. Schlüter, Yu. M. Aliev, M. Moisan, J. Engemann, revealed multiple aspects of the physics of stationary and pulse waveguide discharges, notably the transition from diffusion to atmospheric pressure burning modes alongside associated discharge instabilities. The essence of these studies is the notion that gas discharges have to be treated as nonlinear systems bringing together in a self-consisting manner plasma and electromagnetic field. Based on the results of these investigations, I. Koleva, K. Kirov, Kh. Tarnev, and K. Makasheva received their PhD degrees and A. Shivarova her Doctor of Science in Physics degree. A natural extension are studies of nonlinear wave interactions (including the presence of ionization nonlinearity) that lead to nonstationary states of the discharge (PhD thesis of L. Stoev) and to contraction of the discharge in a filamentous structure (part of the PhD thesis of St. Lishev).

Given the widespread use of radio frequency (rf) capacitive discharges in plasma technology, in the late 90s, E. Tatarova, E. Stoikova, and K. Bachev (members of Plasma Physics Group) experimentally and theoretically studied the transition from weak- (α-) to strong- (γ-) current regime in nitrogen rf capacity discharge with taking into account the non-local kinetics of electrons and also their energy distribution function – the basic results are contained in the PhD thesis of E. Stoikova. Phenomenological model for the energy balance in industrial asymmetric rf capacitive discharge in NF_3, proposed by E. Mateev and I. Zhelyazkov (1999–2004), allows optimization of combustion conditions of the discharge to increase its effectiveness in the process.

Created in 1965 by B. Stefanov Laboratory of Plasma Physics and Engineering at the Institute of Electronics (IE) of BAS (now led by S. Sabchevski) is the largest research unit in plasma physics and plasma technology in BAS. Its field of research is wide-ranging: elementary and transport processes in hot gases and plasma, gas discharges, contemporary diagnostics of equilibrium electric ark plasma and non-equilibrium gas-discharge plasma, plasma chemistry (modelling of physical and chemical processes in plasma jets), design and applications of electric arc plasma sources, plasma technology. In IE of BAS there had been build up a big technological facility (plasmotron) for producing arc plasma suitable for both scientific and applied research. This may be difficult to list all achievements – I will mention only some of them obtained in the last ten years, namely: the new Hohm–Zarkova–Damyanova mixing rule for calculating the second virial coefficient of mixtures of alkanes (PhD thesis of M. Damyanova); deposition of ceramic layers (La–Sr–Mn–O-perovskites) on tubes uniformly coated with yttrium stabilized bismuth (YBi) for cathode elements in solid state oxide fuel cells; construction of a diagnostic device (B. Djakov, D. Oliver, R. Enikov, E. Vasileva) for data processing and monitoring of plasma jet; obtaining nanodispersed SiO_2 in a plasma reactor (E. Balabanova, D. Oliver, A. Levitsky).

2.2 High-temperature fusion plasma

Turning point in the plasma physics research in Bulgaria was the participation of Bulgarian scientists in programs related to the implementation of controlled thermonuclear fusion. The first project of K. Paskalev and co-workers (Faculty of Physics, University of Sofia), started in 1986, was for making automated Fabry–Pérot interferometer for measuring D_α and H_α lines in the fusion reactor T-15 (Moscow). Interferometer has been tested (and approved) on tokamak T-10, but unfortunately unused in T-15 due to reasons beyond the control of Paskalev. Far happier is the fate of two projects of A. Shivarova and members of her Group within Euratom programme on creating self-consistent models of waveguide discharges in hydrogen and inductive discharges – the result is the construction of a two-chamber plasma source (PhD theses of Ts. Paunska and St. Kolev), analogue (miniature) of the rf negative ion source BATMAN in Garching. Research team of Shivarova is now working on a task entitled *Development of Volume Production-Based RF Source of Negative Hydrogen Ions* in the framework of the scientific programme of the Bulgarian EURATOM-INRNE Association – it includes the modeling and diagnostics of two negative hydrogen ions source, based on inductive discharges: tandem-type two-chamber plasma source for ITER and a matrix of small-sized discharges, included in the plan of EFDA to develop a source of negative hydrogen ions without cesium for DEMO. Research results (including diagnostics as well) are summarized in the PhD theses of Ts. Tsankov, St. Lishev, S. Yordanova-Dyulgerova, and M. Christova. Probe diagnostic of fusion plasma is carried out by a team of researchers from the Faculty of Physics, University of Sofia and IE of BAS (M. Dimitrova, P. Ivanova, E. Benova, I. Kotseva, A. Bankova, M. Mitov, K. Tyutyulkov, T. Bogdanov) led by Tsv. Popov whitin the scientific program of EURATOM-INRNE Association – the corresponding task is *Edge Plasma Diagnostics* on using Langmuir probes. Successfully developed automatic diagnostic system was tested on CASTOR and COMPASS tokamaks in Prague, on the ISTTOk tokamak in Lisbon, and on the TJ-II stellarator in Madrid. Various stages of this research are presented in the PhD theses of M. Dimitrova and P. Ivanova. Another team of scientists from IE of BAS and the University (M. Damyanova, E. Vasileva, B. Djakov, V. Atanassov, R. Enikov, P. Dankov, P. Malinov, I. Zhelyazkov) from 2005 onwards has been working on a project of Euratom programme and on a task of the research plan of EURATOM-INRNE Association, notably: *Numerical Investigations of Selected Problems associated with the Development of Powerful Gyrotrons for Fusion Research* and *Development of Numerical Codes to Describe the Behavior of High Power Gyrotrons*. The aim of both studies is the computer modeling of high power gyrotrons (1–2 MW, 170 GHz) for controlled fusion based on adequate self-consistent physical models and their implementation in software program packages using high-effective algorithms, numerical methods, and high-performance computing resources and computing platforms. Research is carried out in cooperation with Institut für Hochleistungsimpuls- und Mikrowellentechnik at Karlsruher Institut für Technologie and Centre de Recherches en Physique des Plasmas at École Polytechnique Fédérale de Lausanne. So far there have been developed two packages, namely GYROSIM (S. Sabchevski, T. Idehara, T. Saito, I. Ogawa, S. Mitsudo, Y. Takematsu) and GYREOSS (M. Damyanova, E. Vasileva, S. Sabchevski, I. Zhelyazkov, S. Kern, S. Illy, M. Thumm) that cover all aspects of computer-aided design of electron-optical and electrodynamical systems of gyrotron. It is worth noticing that on using the GYROSIM package, Sabchevski and his colleagues in Japan have designed sub-terahertz gyrotrons (424 GHz, 100 W) which are used both for basic research but also for applications in medicine and in the processing of new materials.

Two more issues to the plan of EURATOM-INRNE Association are relevant to the diagnostics of fusion plasma, namely: *Improving the Resolution of Thomson Scattering LIDARs by Application of Novel Deconvolution-Based Algorithms* of D. Stoyanov with T. Dreischuh, L. Gurdev, O. Vankov, and Ch. Protochristov at IE of BAS and *Transport of Tungsten Atoms and Ions near the Wall* of A. Blagoev and the members of his research team (K. Blagoev, I. Rusinov, A. Pashov, Z. Peshev, O. Djilianova, S. Zapryanov) at the Faculty of Physics, University of Sofia. Algorithms developed by Stoyanov and his co-workers aim more accurately determination electrons number density and their temperature near the edge and in the center of the JET's (Abingdon) fusion plasma. Investigations of A. Blagoev and colleagues are associated with the measurement by optical methods (also including laser-induced fluorescence) the transport coefficients of tungsten atoms and ions evaporating from tokamak's wall. A. Blagoev with V. Yordanov and S. Zapryanov have been experimenting with plasma focus which can be regarded as a mini thermonuclear device. In his PhD thesis in Physics from 2009, V. Yordanov presented a numerical code (based on the particle-in-cell method, Monte Carlo simulations and the Finite Elements Methods), which yields an adequate description of the electrical breakdown of the gas and the formation of a plasma layer above the dielectric's surface in the first stage of the discharge in a plasma focus type Mather. In the plasma focus, except of detection of neutrons in the result of D–D synthesis, can be formed nanostructures and also to study the influence of the soft X-ray radiation on living organisms – such a research was successfully conducted by A. Blagoev and S. Zapryanov, along with V. Gol'tsev and B. Galutsov (both from the Faculty of Biology, University of Sofia) as the target of X-ray radiation were Chlamydomonas reinhardtii samples.

2.3 Astrophysical plasmas

It is well-established from high-resolution spacecrafts and ground-based observations that the solar atmosphere is magnetically structured and in the so-called magnetic flux tubes one can register high-temperature plasma mass flows of speeds from a few tens to hundreds or thousands of kilometers per second. The concepts of the magnetic flux tube and coronal loops have become increasingly important for understanding explosive phenomena such as solar flares and eruptive prominences. Flowing plasmas support the propagation of different kind of magnetohydrodynamic waves (Alfvén, fast and slow magneto-acoustic ones). The issue of stability of such waves is crucial for clarifying the mechanisms of the solar corona heating. Moreover, the registration of p- and g-mode oscillations in the Sun can be used as a tool for the solar seismology. At the end of the 80s members of Plasma Physics Group (Zh. Kiss'ovski, W. Sahyouni, P. Edwin, P. Nenovski, I. Zhelyazkov) explored the possibility of heating the chromosphere and coronal plasma by dissipation of fast magneto-acoustic surface waves. The results of these studies are synthesized in the PhD thesis of W. Sahyouni, in which in addition is discussed the possibility for detection of dark envelope solitons of the fast magneto-acoustic waves propagating in magnetic flux tubes of the solar atmosphere. Another issue was the study of the dispersion characteristics and stability status of fast magnetohydrodynamic waves in the solar wind in the framework of the so-called Hall magnetohydrodynamics (1995–2010) – the results of these studies, obtained by R. Miteva, I. Zhelyazkov, A. Debosscher, M. Goossens, G. Mann, R. Erdélyi, H. Sikka, and N. Kumar, have appeared in several of the most recognized plasma physics journals. Newly received data by observational satellites *Hinode* (Japan) and *Solar Dynamic Observatory* (US) provided a wealth of material to study the stability of photospheric, chromospheric and coronal jets. In particular it was found that at a critical velocity of the plasma in chromospheric and soft X-ray jets an instability of Kelvin–Helmholtz-type arises (I. Zhelyazkov, T. V. Zaqarashvili), which serves as a trigger for the occurrence of wave turbulence, leading to heating of the solar corona.

T. Mishonov (Department of Theoretical Physics at Faculty of Physics, University of Sofia), along with a PhD student and post-graduate students explore the possibility of the solar corona heating through the dissipation of Alfvén waves, and also investigate the waves propagation and instabilities in astrophysical plasma flows. Z. Dimitrov's PhD thesis (2013), which studies magnetohydrodynamic waves and instabilities in a shear flow of magnetized plasma of low viscosity, is one of the few cases (if not only), in which starting from the basic set of magnetohydrodynamic equations one works out, in a self-consistent way, the emergence of wave turbulence and a giant effective viscosity. If this solution would be generalized for rotating plasma, we will have a solution to the problem of transfer of angular momentum – the primary problem of the physics of stars formation.

3 Programmes in Plasma Physics

Training of the scientific staff of plasma physics has began in the Faculty of Physics, University of Sofia at the end of the 70s and continues to this day. Wide range of lectures (with different workload and stress) were/are given by I. Zhelyazkov, A. Shivarova, B. Djakov, S. T. Ivanov, A. Blagoev, T. Mishonov, E. Benova, Tsv. Popov; the basic courses in plasma physics of Zhelyazkov and Shivarova included/include laboratory practicum and/or seminars. The important part in this process have scientists from ISSP and IE of BAS in training of post-graduate and PhD students in plasma and gas-discharge physics. E. Benova is Head of the Master's Programme *Fusion and Plasma Technology* within the project FuseNet (The European Fusion Education Network), which aims to establish a pan-European masters and doctoral programme in fusion and plasma technology. This internet education network involves 22 universities, 14 Euratom associations, and ITER. Indicative for the prestige of the Bulgarian plasma physics community are conducted biennials International Workshop & Summer School on Plasma Physics in Kiten (organized and run by E. Benova, University of Sofia) and School and Workshop on Space Plasma Physics on Bulgarian Black Sea coast, organized by I. Zhelyazkov and T. Mishonov (University of Sofia), and, of course, the International Summer School on Vacuum, Electron, and Ion Technologies in Sozopol (organized and run by N. Guerassimov and M. Dimitrova, IE of BAS) where contributions to plasma physics and plasma technology are reported, too.

4 Conclusion and Outlook

What are the prospects of plasma physics research in our country? The answer to this rhetorical question is clear: cooperation of research groups with leading European and international universities and institutions in the research programmes of the European Commission (Euratom, FuseNet), European Space Agency, Inter-Academia, as well as bilateral agreements for scientific and technical cooperation. Scientific potential of Bulgarian plasma-physicists, including in addition the youngest generation, ensure successful resolution of complex problems of ecology, space weather, medicine. The introduction of plasma-technology developments in industry in the country (and abroad) would help to significantly improve the material and technical base of scientific and applied research in plasma physics in Bulgaria.

For excellence of A. Shivarova in plasma physics, she was awarded (2004) the prize of the Alexander von Humboldt Foundation, and for scientific contributions of E. Benova to the physics of microwave discharges from 2002 onwards she was a member of the International Scientific Committee of the International Workshop on Microwave Discharges: Fundamentals and Applications.