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Modern Methods in Plasma Spectroscopy

Summary Report of Joint ICTP-IAEA Advanced School and Workshop

Trieste, Italy

16-27 March 2015

Prepared by

H.-K. Chung, Yu. Ralchenko and B. J. Braams

June 2015

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ABSTRACT

This report summarizes the proceedings of the Joint ICTP-IAEA Advanced School and Workshop on Modern Methods in Plasma Spectroscopy. 67 participants from 16 Member States including one from the ITER organization and one from ICTP as well as two from the IAEA attended the two-week event held at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy. The purpose of the School and Workshop was to provide training and information exchange for plasma physicists, plasma spectroscopists, and other users of atomic data for fusion, astrophysics and laser and plasma applications to expand their knowledge of plasma spectroscopy and associated atomic science.

May 2015

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INTRODUCTION

The Abdus Salam International Centre for Theoretical Physics (ICTP) and the International Atomic Energy Agency (IAEA) jointly organized the Advanced School and Workshop on Modern Methods in Plasma Spectroscopy at ICTP in Miramare, Trieste, Italy, from 16 to 27 March 2015. The purpose of the event was to provide training and information exchange for plasma physicists, plasma spectroscopists, and other users of atomic data for fusion, astrophysics and laser and plasma applications in order to expand their knowledge of plasma spectroscopy and associated atomic science. The Advanced School in the first week brought together experts in experimental and theoretical plasma spectroscopy to train early-career plasma scientists in the most recent developments and results in the field. The Workshop in the second week provided opportunities for participants to present their work, discuss current needs in plasma diagnostics, and motivate further developments.

During the advanced school, 10 lecturers gave 18 lectures including 4 computer trainings. The lecturers were E. Behar (Technion, Israel), H.-K. Chung (IAEA, Austria), C. J. Fontes (LANL, USA), P. Jönsson and J. Ekman (Malmö Univ, Sweden), K. Koshelev (ISRAS, Russian Federation), H.-J. Kunze (Ruhr Univ, Germany), O. Marchuk (FZ Jülich, Germany), Yu. Ralchenko (NIST, USA) and H. A. Scott (LLNL, USA).

During the 2nd week of the workshop, 24 invited speakers presented their current work involving applications and theoretical developments of plasma spectroscopy in the fields of laser plasmas, magnetic fusion plasmas, astrophysics and pulsed power machines. The invited speakers were Y. Aglitskiy (NRL, USA), R. Barnsley (ITER Organization, France), S. Bastiani-Ceccotti (LULI, France), E. Behar (Technion, Israel), B. J. Braams (IAEA, Austria), S. Brezinsek (FZJ, Germany), B. I. Cho (GIST, South Korea), H. K. Chung (IAEA, Austria), R. Dux (IPP-Garching, Germany), C. J. Fontes (LANL, USA), J. Ghosh (IPR, India), M. Goto (NIFS, Japan), J. Kaastra (SRON, Netherlands), Y. Maron (Weizmann Inst. Sci., Israel), H. Nishimura (Osaka Univ., Japan), M. O'Mullane (Strathclyde Univ., UK), R. Prakash (CEERI, India), Yu. Ralchenko (NIST, USA), O. Renner (FZU, Czech Republic), D. W. Savin (Columbia Univ., USA), H. A. Scott (LLNL, USA), E. Stambulchik (Weizmann Inst. Sci., Israel), S. Vinko (Oxford Univ., UK) and U. Zastrau (Jena Univ., Germany).

A total of 37 participants attended the advanced school, the workshop or both and they presented 32 posters and 6 contributed talks. The contributed presentations were given by G. Avaria (CCHEN, Chile), G. D’Ammando (CNR, Italy), H. M. Johns (LANL, USA), T. V. Tsankov (Ruhr Univ., Germany), M. Koubiti (Univ. of Aix-Marseille, France) and S. Varshney (ITER-India, India). The participants had been selected from more than 170 applications at the ICTP registration site.

Proceedings of the Advanced School and Workshop and discussion sessions are summarized here. Appendix 1 provides the list of participants. The meeting agenda is given in Appendix 2 and abstracts provided by participants are found in Appendix 3.

PROCEEDINGS

The Advanced School started with welcome remarks from the directors. The first two lectures provided a survey of theoretical (Ralchenko) and experimental (Kunze) plasma spectroscopy. They were followed by lectures on atomic physics including atomic structure, radiative processes, atomic collisions and line shapes and broadening (Ralchenko, Ekman, Jönsson). An extensive overview was provided of plasma diagnostic methods (Kunze). Lectures were given on plasma diagnostics used in various fields: industrial plasmas, magnetic fusion plasmas, dense plasmas, and astrophysical plasmas (Koshelev, Marchuk, Chung, Behar). The related topics of radiation transport and opacities were presented as well (Scott, Fontes). On Friday 20 March 2015, Prof. Behar's lecture on spectroscopic diagnostics of astrophysical plasmas was open to the wider audience of ICTP. Four computer training labs were held on two Linux-based codes (GRASP2K and CRETIN) and two online-based codes (FLYCHK and LANL atomic physics codes).
Poster sessions open at the end of the day on Monday and Wednesday were highly successful and 31 Advanced School participants interacted very well to learn from each other. The computer labs were very useful too, but most participants found them rather short, particularly for those who are not familiar with Linux systems.

At the end of the school in the first week participants were asked to fill out a feedback form. Also there was a short open session to discuss what can be improved for the next advanced school. The databases and data activities of the Atomic and Molecular data unit (Unit) were described for the Advanced School participants and the importance of evaluation activities was emphasized. New and interesting problems were discussed in the field of plasma spectroscopy such as plasmas generated by x-ray free electron lasers (XFEL), high harmonics lights, ultrashort high intensity lasers, high charged ions generated in electron beam ion traps (EBIT), laboratory astrophysics, and precision spectroscopy to study QED effects etc. Theories for three dimensional radiation transport, transient matters or studies bridging two states of matter, equation of states, magnetic fields in short time scales etc are also rapidly developing.

19 participants and 4 lecturers of the School stayed on for the workshop in the second week and a total of 46 scientists participated in the 5-day workshop. The Workshop began with the welcome remarks from the directors. On Monday, presentations were given on the topic of magnetic fusion plasmas (R. Dux), laser produced plasmas (H. Nishimura, Y. Aglitskiy) as well as x-ray free electron laser plasmas (S. Vinko, B.I. Cho) and the day ended with a poster session. On Tuesday ICTP director J. Niemela gave an introduction to ICTP activities. Invited presentations were mainly related to atomic properties (C. J. Fontes, E. Stambulchik), radiation transport (H. A. Scott) and astrophysical plasmas (J. Kaastra, Yu. Ralchenko, E. Behar). Contributed presentations by G. F. Avaria, G. D'Ammando, H. M. Johns and T. V. Tsankov were given. On Wednesdaymorning invited presentations on magnetic fusion (R. Barnsley, M. Goto), pulsed power (Y. Maron) and industrial plasmas (R. Prakash) were given; Wednesday afternoon was free. On Thursday, invited presentations on magnetic fusion plasmas (S. Brezinsek, J. Ghosh) and high energy density physics plasmas (U. Zastrau, O. Renner, S. Bastiani-Ceccotti, H. Chung) were given as well as 2 contributed talks (M. Koubiti, S. Varshney). On Friday, invited presentations related to data activities (M. O'Mullane, D. W. Savin and B. J. Braams) were given.

There was a discussion session on Thursday afternoon and Friday morning reviewing the status of plasma spectroscopy, scientific challenges and the benefit of the workshop.

More details of presentations by Workshop participants can be found from the Abstracts in the Appendix 3. Presentation materials from both school and workshop are available at the Unit's webpage, www-amdis.iaea.org/Workshops/ICTP2015.

CONCLUSIONS AND RECOMMENDATIONS

It is a challenge to keep up with the rapid development of experimental and theoretical techniques for spectroscopic diagnostics and their application in new or upgraded international (ITER) and national fusion machines, new space observatories and new laser user facilities. The Advanced School and Workshop provided a comprehensive yet reasonably compact overview of modern plasma spectroscopy for the analysis and understanding of plasma behaviour in fusion experiments, industrial devices, extraterrestrial objects, and warm and hot dense matter. We think that it was valuable to assemble a cross section of young and established researchers from these disciplines. In any case, the event was much appreciated by the participants.

Scientifically, there have been great advances in technology enabling simulations for complex problems and improving experimental techniques. One finds that not only the production and distribution of atomic data is important, but also storing and saving data for complex simulations, that is, the curation of data, becomes increasingly important. Recently, an emphasis has been placed in understanding of uncertainty estimates of theoretical results. Particularly, collisional-radiative models and line shape calculations have improved over the years and there exist reasonably good tools for validation and verification of their results. Experimentally, plasma spectroscopy plays a critical role in understanding novel plasma states created with XFELs, space laboratories, intense z-pinches and other facilities with greatly improved detectors and spectrometers. There exist scientific challenges such as the ionization potential depression (IPD) phenomenon that bridges atomic physics to condensed matter physics with plasma physics in between. For magnetic fusion, plasma spectroscopy is used for general diagnostics and erosion measurements of plasma facing materials and the analysis of spectroscopic data using photon efficiency needs more work.

The questionnaire at the end of the first week provided valuable concrete feedback on the school that we will keep in mind for a future similar event. Many students expressed strong appreciation of the school and nobody was negative about the event. The fundamental talks and the computer labs were most appreciated. The lectures on experimental spectroscopy are an essential part of the school; multiple participants asked for more attention to experimental spectroscopy and no-one asked to just focus on the theory or the codes. Also, many participants asked for more time in the computer labs. In general, if participants commented on the level of the school then they asked for more attention to the basics, e.g. basic electronic structure theory. Effort can be made to achieve a better coordination among lectures; better coordination of sequencing, less overlap of subjects, clearer progress from elementary to advanced topics over the course of the week. The computer labs need more preparation and help with setup, with some information distributed already before the school. The experimental data analysis part was missing the School program and a lecture on data, for example, definition and handling of data, was suggested. Plasma spectroscopy experiment class was also mentioned as a part of the future program but this would require the use of a laboratory facility.

Participants expressed that the workshop was educational and instructive by bringing experts from a very broad areas of plasma spectroscopy together to learn from each other. There was a suggestion to consider inviting solid state spectroscopy, which shares common interest especially for warm dense matter studies. Organizationally, a suggestion was made to organize the event with lectures in the mornings and special topics in the afternoons so that senior scientists in the field can also benefit from the lectures on various subjects. In order to continue the format, financial arrangements will be necessary for participants from developing countries. An idea of working on a problem together during the workshop came up such as is done in the Non-LTE (local thermodynamic equilibrium) kinetics workshops. An online forum to exchange information on plasma spectroscopy methods was suggested.

There are common problems facing plasma spectroscopy community over a broad range of applications; they include funding issues, a lack of students as well as poor working prospects for students. For ITER, there are enough students who want to learn and use plasma spectroscopy, however, in the other areas, the number of students enrolled in the classes has decreased significantly and hence the dedicated lectures and classes are hard to find in most universities. It is rather an international trend and it is strongly suggested that an international organization such as IAEA or ICTP should pay special attention to this issue and establish a programme for students and young scientists. There is a need for training courses on basics of plasma spectroscopy in addition to advanced training courses such as this event.

APPENDIX 1: Participants

Directors

1. B. J. Braams (International Atomic Energy Agency, Austria)
2. H.-K. Chung (International Atomic Energy Agency, Austria)
3. J. Niemela (Abdus Salam International Centre for Theoretical Physics, Italy)
4. Yu. Ralchenko (National Institute of Standards and Technology, USA)

Speakers and Lecturers

5. Y. Aglitskiy (Naval Research Laboratory, USA)
6. R. Barnsley (ITER Organization, France)
7. S. Bastiani-Ceccotti (Ecole Polytechnique, France)
8. E. Behar (Technion Institute of Technology, Israel)
9. S. Brezinsek (Forschungszentrum Jülich GmbH, Germany)
10. B. I. Cho (Gwangju Institute of Science and Technology, South Korea)
11. R. Dux (Max Planck Institut fur Plasmaphysik-Garching, Germany)
12. J. Ekman (Malmö University, Sweden)
13. C. J. Fontes (Los Alamos National Laboratory, USA)
14. J. Ghosh (Institute for Plasma Research, India)
15. M. Goto (National Institute of Fusion Science, Japan)
16. P. Jönsson (Malmö University, Sweden)
17. J. Kaastra (SRON Netherlands Institute for Space Research, Netherlands)
18. K. Koshelev (RAS Troitsk, Russian Federation)
19. H.-J. Kunze (Ruhr University Bochum, Germany)
20. O. Marchuk (Forschungszentrum Jülich GmbH, Germany)
21. Y. Maron (Weizmann Institute of Sciences, Israel)
22. H. Nishimura (Osaka University, Japan)
23. M. O'Mullane (University of Strathclyde, UK)
24. R. Prakash (Central Electronics Engineering Research Institute, India)
25. O. Renner (Academy of Sciences of the Czech Republic, Czech)
26. D. W. Savin (Columbia University, USA)
27. H. A. Scott (Lawrence Livermore National Laboratory, USA)
28. E. Stambulchik (Weizmann Institute of Sciences, Israel)
29. S. Vinko (Oxford University, UK)
30. U. Zastrau (Friedrich Schiller University Jena, Germany)

School and Workshop Participants

31. V. Aslanyan (University of York, UK)
32. G. F. Avaria (Chilean Nuclear Energy Commission, Chile)
33. G. A. Beyene (University College Dublin, Ireland)
34. C. Brandt (Forschungszentrum Jülich GmbH, Germany)
35. M. Carr (Culham Centre for Fusion Energy, UK)
36. U. P. Chaulagain (LERMA, Observatoire de Paris, France)
37. G. D’Ammando (Consiglio Nazionale delle Ricerche, Italy)
38. T. Das (National Institute of Standards and Technology, USA)
39. S. K. Dass (ITER-INDIA,Institute for Plasma Research, India)
40. X. Ding (Northwest Normal University, China)
41. Dipti (Indian Institute of Technology Roorkee, India)
42. T. G. Donnelly (Trinity College Dublin, Ireland)
43. M. Dozieres (Commissariat à l'énergie atomique et aux énergies, France)
44. M. Gavrilovic (University of Belgrade, Serbia)
45. I. Gissis (Technion Institute of Technology, Israel)
46. Bo Han (National Astronomical Observatories, Chinese Academy of Science, China)
47. D. Heunoske (Fraunhofer Institut für Kurzzeitdynamik, Germany)
48. H. M. Johns (Los Alamos National Laboratory, USA)
49. L. Juschkin, (RWTH Aachen University, Germany)
50. K. Kurchikov (Lomonosov Moscow State University, Russia)
51. M. Koubiti (CNRS-Aix-Marseille Universite, France)
52. M. Ladygina (Kharkov Institute of Physics and Technology, Ukraine)
53. W. Lee (Korea Atomic Energy Research Institute, Korea)
54. N. Nimavat (Institute for Plasma Research, India)
55. M. D. Nornberg (University of Wisconsin-Madison, USA)
56. U. Peretz (Technion Institute of Technology, Israel)
57. J. Raud (Tartu University, Czech Republic)
58. S. Sapna Mishra (ITER-India Institute for Plasma Research, India)
59. J. P. Simoes Loureiro (Instituto de Plasmas e Fusão Nuclear, Portugal)
60. M. Su (Northwest Normal University, China)
61. D. Sun (Northwest Normal University, China)
62. M. Tomes (Academy of Sciences of the Czech Republic, Czech Republic)
63. T. V. Tsankov (Ruhr University Bo.., Germany)
64. K. Tsigutkin (ASML, Netherlands)
65. S. Varshney (ITER-India, India).
66. Y. Yang (Fudan University, China)
67. D. R. Zaloga (National Centre for Nuclear Research, Poland)

APPENDIX 2: Meeting Agenda

Advanced School on Modern Methods in Plasma Spectroscopy

Monday, 16 March 2015

08:30 - 09:30	**E. Brancaccio**: Registration and administrative formalities in the Main Lobby, Leonardo da Vinci Building.
09:30 - 10:00	**Directors**: Welcome and introduction of participants.
10:00 - 10:30	**Yu. Ralchenko, NIST, Gaithersburg, MD, USA**: Overview of plasma spectroscopy
10:30 - 11:00	*Break*
11:00 - 12:00	**H.-J. Kunze, Ruhr-University, Bochum, Germany**: Experimental spectroscopy
12:00 - 13:30	*Lunch*
13:30 - 14:30	**J. Ekman and P. Jönsson, Malmö University, Sweden**: Atomic structure calculations: fundamental concepts
14:30 - 15:30	**Yu. Ralchenko**: Radiative processes (Continuation of earlier Overview lecture.)
15:30 - 16:00	*Break*
16:00 - 17:30	**All**: Poster Session. See below. Posters can remain up throughout the event.
17:30 - 19:00	*Welcome reception*

Tuesday, 17 March 2015

09:00 - 10:00	**H.-J. Kunze**: Diagnostic applications
10:00 - 10:30	**Yu. Ralchenko**: Atomic collisions
10:30 - 11:00	*Break*
11:00 - 11:30	**Yu. Ralchenko**: Atomic collisions (continued).
11:30 - 12:30	**J. Ekman and P. Jönsson**: Atomic structure calculations using GRASP2K
12:30 - 14:00	*Lunch*
14:00 - 15:30	**J. Ekman and P. Jönsson**: Computer lab 1: GRASP2K. (External link to multiple materials.)
15:30 - 16:00	*Break*
16:00 - 17:00	**C. J. Fontes, LANL, Los Alamos, NM, USA**: Computer lab 2: ATOMIC.

Wednesday, 18 March 2015

09:00 - 10:00	**E. Behar, Weizmann Institute of Science, Rehovot, Israel**: Atomic processes in plasmas.
10:00 - 10:45	**Yu. Ralchenko**: Line shapes and broadening
10:45 - 11:15	*Break*
11:15 - 12:15	**C. J. Fontes**: Opacity and emissivity.
12:15 - 13:30	*Lunch*
13:30 - 14:30	**H. A. Scott, LLNL, Livermore, CA, USA**: Radiation transport
14:30 - 15:00	**K. Koshelev, Troitsk, Russian Federation**: Industrial plasma - is it something to respect?
15:00 - 15:30	*Break*
15:30 - 16:30	**K. Koshelev**: Industrial plasma (continued).
16:30 - 17:30	**All**: Poster session (continued).

Thursday, 19 March 2015

09:00 - 09:45	**O. Marchuk, Forschungszentrum Jülich GmbH, Jülich, Germany**: Magnetic fusion spectroscopy
09:45 - 10:30	**H.-K. Chung, IAEA, Vienna, Austria**: Spectroscopy of dense plasmas
10:30 - 11:00	*Break*
11:00 - 11:45	**C. J. Fontes**: Mean opacity.
11:45 - 12:30	**H. A. Scott**: Radiation transport (continued).
12:30 - 14:00	*Lunch*
14:00 - 15:30	**H. A. Scott**: Computer lab 3: CRETIN.
15:30 - 16:00	*Break*
16:00 - 17:00	**H.-K. Chung**: Computer lab 4: FLYCHK

Friday, 20 March 2015

09:00 - 10:00	**E. Behar**: Astrophysical plasmas. (Special lecture for wider audience, held in the Budinich lecture hall.)
10:00 - 11:00	*Break and Solar Eclipse Session*
11:00 - 12:00	**O. Marchuk**: Magnetic fusion spectroscopy (continued).
12:00 - 12:30	**All**: Conclusions.
12:30	*School adjourns*

Workshop on Modern Methods in Plasma Spectroscopy

Monday, 23 March 2015

08:30 - 09:00	**E. Brancaccio**: Registration and administrative formalities in the Main Lobby, Leonardo da Vinci Building.
09:00 - 09:40	**Directors**: Welcome on behalf of IAEA, Overview of the workshop, and introduction of participants.
09:40 - 10:20	**R. Dux, IPP Garching, Germany**: Active spectroscopy on the neutral beams in ASDEX Upgrade.
10:20 - 11:00	*Break*
11:00 - 11:40	**H. Nishimura, Osaka University, Japan**:
11:40 - 12:20	**Y. Aglitskiy, NRL, USA**: Analysis of X-ray Nike spectra from highly charged high-Z ions
12:20 - 14:00	*Lunch*
14:00 - 14:40	**S. Vinko, Oxford University, UK**:
14:40 - 15:20	**B. I. Cho, GIST, Gwangju, Korea**: Reverse saturable absorption of intense X-ray pulses in aluminum.
15:20 - 16:00	*Break*
16:00 - 17:30	**All**: Poster session. See below. Posters can remain up throughout the event.
17:30 - 19:00	**All**: Reception.

Tuesday, 24 March 2015

09:00 - 09:10	**J. Niemela, ICTP, Trieste, Italy**: Welcome on behalf of ICTP.
09:10 - 09:50	**C. J. Fontes, LANL, Los Alamos, NM, USA**: Opacities for neutron star mergers.
09:50 - 10:30	**H. A. Scott, LLNL, Livermore, CA, USA**: Spectroscopic investigations of implosions on the National Ignition Facility
10:30 - 11:00	*Break*
11:00 - 11:40	**J. Kaastra, SRON, Utrecht, The Netherlands**: Progress in modeling astrophysical plasmas
11:40 - 12:20	**Yu. Ralchenko, NIST, Gaithersburg, MD, USA**: Detailed spectra modeling in low-density plasmas
12:20 - 14:00	*Lunch*
14:00 - 14:40	**E. Behar, Haifa, Israel**:
14:40 - 15:20	**E. Stambulchik, Weizmann Institute of Science, Rehovot, Israel**: Lineshape modeling for collisional-radiative calculations
15:20 - 16:00	*Break*
16:00 - 16:20	**Gonzalo Filipe Avaria, CCHEN, Santiago, Chile**:
16:20 - 16:40	**G. D'Ammando, CNR and University of Bari, Italy**: Radiation transport, fluid dynamic and collisional-radiative model of radiative shock waves in H2/He mixture for aerospace and astrophysical plasmas
16:40 - 17:00	**H. M. Johns, LANL, Los Alamos, NM, USA**: Improved collisional line broadening for low temperature ions and neutrals in the plasma modelling code ATOMIC
17:00 - 17:20	**T. V. Tsankov, Ruhr University, Bochum, Germany**: Atomic processes in low pressure argon afterglows.

Wednesday, 25 March 2015

09:00 - 09:40	**R. Barnsley, ITER Organization, France**: ITER spectroscopic diagnostics
09:40 - 10:20	**M. Goto, NIFS, Toki, Japan**:
10:20 - 11:00	*Break*
11:00 - 11:40	**Y. Maron, WIS, Rehovot, Israel**: Experimental discrimination between ion temperature and hydromotion in turbulent plasma
11:40 - 12:20	**R. Prakash, CEERI, Pilani, Rajasthan, India**: Simultaneous Estimations of Plasma Parameters using Quantitative Spectroscopy
12:20	*Free time*

Thursday, 26 March 2015

09:00 - 09:40	**S. Brezinsek, Forschungszentrum Jülich GmbH, Jülich, Germany**: Atomic and molecular spectroscopy in the scrape-off layer of high temperature fusion plasmas, results from TEXTOR and JET
09:40 - 10:20	**J. Ghosh, IPR, India**:
10:20 - 11:00	*Break*
11:00 - 11:40	**U. Zastrau, Jena and Hamburg, Germany**: Electron trapping by strong Coulomb coupling in a relativistic laser plasma
11:40 - 12:20	**O. Renner, FZU, Czech Republic**: Hot electron production at shock-ignition-relevant conditions characterized by high resolution spectroscopy and imaging
12:20 - 14:00	*Lunch*
14:00 - 14:40	**S. Bastiani-Ceccotti, LULI, France**:
14:40 - 15:20	**H.-K. Chung, IAEA, Vienna, Austria**: Atomic processes in dense plasmas
15:20 - 16:00	*Break*
16:00 - 16:20	**M. Koubiti, University of Aix-Marseille, France**:
16:20 - 16:40	**S. Varshney, ITER-India, India**:
16:40 - 17:20	**All**: Discussion.

Friday, 27 March 2015

09:00 - 09:40	**M. O'Mullane, University of Strathclyde, UK**: Assembling atomic data for diagnosing and modelling fusion plasmas
09:40 - 10:20	**D. W. Savin, Columbia University, New York, NY, USA**: A review of cosmically motivated measurements for atomic ionization and recombination using ion storage rings
10:20 - 11:00	*Break*
11:00 - 11:40	**B. J. Braams, IAEA, Vienna, Austria**: Steps towards uncertainty estimates for calculated atomic and molecular data
11:40 - 12:20	**All**: Discussion.
12:20	*Workshop adjourns*

Active Spectroscopy on the Neutral Beams in ASDEX Upgrade

R. Dux, M. Cavedon, B. Geiger, A. Kappatou, A. Lebschy, R.M. McDermott, T. Pütterich, E. Viezzer

Max-Planck-Institut für Plasmaphysik, Garching, Germany.

On the ASDEX Upgrade tokamak, eight beams of fast deuterium atoms with kinetic energies of up to 93keV and a power of 2.5MW per beam are used to heat the plasma. The beam diameters are about 30cm. Several optical heads comprising some 200 lines-of-sight are used to observe three beams. The observed intersection volumes of beams and the lines-of-sight have diameters of a few mm up to 3cm depending on the required spatial resolution. Silica fibres guide the light from the optical heads out of the tokamak vessel and the experimental hall to a suite of 12 spectrometers, which record the spectra with a temporal resolution ranging from of a few ms down to 50µs.

This large experimental effort is motivated by the main advantage of active spectroscopy, i.e. the possibility to obtain local measurements with good spatial resolution. Furthermore, charge exchange reactions between D and fully ionised impurities lead to visible radiation from the recombining ion, which allows for the determination of impurity densities that are otherwise not accessible by spectroscopic observation. Most of the spectrometers are used for this measurement technique called Charge EXchange Recombination Spectroscopy (CXRS), by which the light elements between He and Ne are usually studied. The radiance, width and shift of the emission lines deliver impurity ion density, temperature and rotation velocity. Combined measurements of poloidal and toroidal fluid velocities yield the radial electric field via the force balance equation. For CXRS with He^{2+}, the recombined ion can be excited by electron collisions before re-ionisation takes place and thus emit another photon. This leads to a delocalised contribution to the active signal, whose influence on line shape and line strength has lately been resolved using an elaborate Monte-Carlo model. The non-thermal fast ion population of D^+ is studied by measuring the Dα radiation from the recombined ion at a correspondingly large Doppler shift. Also here, a Monte Carlo code is used for a quantitative analysis of the signal.

The Dα emissions from excited atoms within the neutral beams contain important information and are recorded with 3 spectrometers. Due to the large atom velocities and the strong magnetic field in the tokamak, there is a large electric field in the rest frame of the atoms and the up in a spectrum with 9 strong lines and 6 very weak lines. The line splitting and the polarisation dependence of the emission from individual lines can be used to determine the magnetic field direction. The total line strength gives information on the neutral beam density, which is attenuated along the beam path in the plasma. It replaces the beam density from attenuation calculations whose uncertainty is increasing with increasing path length. Thus, the uncertainty of the impurity density evaluation is reduced by these measurements. The beam attenuation is caused by ionisation and charge exchange collisions. The charge exchange between plasma D ions and beam neutrals leads to a cloud of thermal D neutrals around the beam, known as the beam halo. The Dα emission from the beam halo is usually the prominent feature of the measured spectra and it turns out that charge exchange between halo atoms and impurities can lead to a rather large contribution of the active CXRS signal (up to 40%) and needs to be included in the evaluation.

The talk will give an overview of the spectroscopic techniques employed at ASDEX Upgrade with emphasis on the methods described above.

Quantitative x-ray spectroscopy for energy transport in fast ignition plasma driven with LFEX PW laser

H. Nishimura[a], Z. Zhang[a], T. Ikenouchi[a], S. Fujioka[a], Y. Arikawa[a], M. Nakai[a], H. Chen[b], J. Park[b], G. J. Williams[b], T. Ozaki[c], H. Shiraga[a], S. Kojima[a], H. Hosoda[a], N. Miyanaga[a], J. Kawanaka[a], Y. Nakata[a], T. Jitsuno[a] and H. Azechi[a]

a) Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan
b) Lawrence Livermore National Laboratory, Livermore, California 94550, USA
c) National Institute for Fusion Science, LHD, High Temperature Plasma G. 322-6 Oroshi Toki, Gifu 509-5292, Japan

Kα emission, caused by hot electrons propagation in a hot dense matter, can provide abundant information about the laser plasma interaction. Quantitative Kα line spectroscopy is a potential method to derive energy transfer efficiency from laser to hot electrons. A Laue spectrometer, composed of a cylindrically curved crystal and a detector, has been developed and calibrated absolutely for high energy x-rays ranging from 17 to 77 keV. Either a visible CCD detector coupled to a CsI phosphor screen or a sheet of imaging plate can be chosen as detector. The absolute sensitivity of the spectrometer system was calibrated using pre-characterized laser-produced x-ray sources and radioisotopes [1], for the detectors and crystal respectively. The integrated reflectivity for the crystal is in good agreement with predictions by an open code for x-ray diffraction.

The energy transfer efficiency from incident laser beams to hot electrons, as the energy transfer agency is derived as a consequence of this work [2]. The absolute yield of Au and Ta Kα lines were measured in the fast ignition experimental campaign performed at ILE Osaka U.. By applying the electron energy distribution from an electron spectrometer (ESM) or a high energy x-ray spectrometer (HEXS), energy transfer efficiency of incident LFEX, a kJ-class PW laser, to hot electrons was derived. Recently, double tracer method was also investigated to avoid complication arising from experimental data on hot electron temperatures measured with ESM and HEXS.

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KrF Nike Laser as a Powerful Platform for Experimental X-Ray Spectroscopy of High-Z Ions

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The NRL Nike laser is capable of delivering several kilojoules of ultraviolet light (λ = 248 nm) on a target within several nanoseconds which is sufficient to produce high-Z ions with multi-keV ionization potentials. As such this system is a unique platform to benchmark high-energy-density plasma diagnostics and relevant atomic physics simulations.

For this purpose two high-resolution x-ray spectrometers have been added to the Nike diagnostic suite. One is a survey instrument covering the spectral range from 0.5 to 19.5 angstroms, and the other is an imaging spectrometer using a spherically curved crystal. The survey instrument allows simultaneous high-spectral-resolution observations of both K- and L-spectra up to Z= 30, L- and M-ones to 50 and M- and N-spectra of highly-charged ions with nuclear charge Z=70-85. The imaging spectrometer provides even more detailed spectra within a narrower variable spectral band with a substantially higher efficiency. Measurements and analyses of isoelectronic sequences from several elements greatly assist in identification of specific spectral lines that are of major interest.

One of the goals of this study of x-ray spectra is to provide more insight into the M-band contribution to the total energy balance inside hohlraums of indirect laser fusion experiments. The Nike shots taken with a power density of 2×10^{14} W/cm^2 on the foils of Hf, Ta, W, Pt, Au and Bi confirmed presence of strong spectral lines from Ni-like ions along with multiple satellite lines originating from the lower stages of ionization. High-quality n=2-n=3 spectra from L-shell ions of elements from Y to Sn were also measured for calibration and testing.

Simulations of the measured spectra were performed with the collisional-radiative code NOMAD. The atomic data including level energies, radiative and autoionization transition probabilities, and collisional cross sections were calculated with the relativistic Flexible Atomic Code by Gu. A typical simulation would include about six ionization stages with a total of ~30,000 atomic levels. The effects of ionization potential lowering and opacity were taken into account as well. The synthetic spectra will be compared with the measured data. The typical values of electron temperature and density derived from comparisons are on the order of 2000 eV and 10^{21} cm^{-3}.

Measuring fundamental properties of dense plasmas on X-ray Free-Electron Lasers

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The past few years have seen a revolution in the field of X-ray science. The advent of the world's first hard X-ray free-electron laser (FEL) – the Linac Coherent Light Source free-electron laser at SLAC – in one step in 2009 increased the spectral brightness of X-ray sources over that of any synchrotron on the planet by a factor of a billion. Spatially coherent, monochromatic, femtosecond X-ray pulses can now be routinely produced over a wide spectral range, enabling access to spatial and temporal scales of atomic processes in plasmas simultaneously for the first time. Importantly, focused FEL pulses are intense enough to create solid-density plasmas at temperatures of several 100 eV on ultra-short, inertially confined timescales, akin to the conditions found half-way into the centre of the sun [1]. The capability of creating such systems in a controlled manner has allowed for the first detailed measurements of several fundamental properties of dense plasmas, such as the ionization potential depression [2,3] and electron collisional ionization rates [4]. Here I will discuss some of these advances and show how obtaining accurate experimental data in the notoriously challenging dense-plasma regime is needed to advance our understanding of systems of crucial importance to a range of astrophysical and inertial confinement fusion investigation

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Reverse Saturable Absorption of Intense X-ray Pulses in Aluminum

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Reverse saturable absorption (RSA) is the property of matter where the optical absorbance increases with increasing light intensity. It is a well-known optical phenomenon, but has not been observed in x-ray regime, where fast non-radiative core-electron transitions typically dominate population kinetics during light-matter interactions. In this talk, I will discuss the observation of the decreasing transmission of intense XFEL pulses with 10^{17} W/cm^2 at the below K-absorption edge of aluminum. XFEL pulses interacting with solid aluminum sample are modelled using the collisional-radiative code SCFLY. Intensity dependent x-ray absorption / transmission could be ascribed to the resonant absorption channel, and the detailed population kinetics and relevant sample conditions will be discussed.

Opacities for Neutron Star Mergers

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Ongoing efforts to improve and expand the relativistic capabilities in the Los Alamos suite of atomic physics codes have produced a more robust approach that can accommodate larger fine-structure models with configuration interaction. The use of this capability to generate opacities that are relevant for astrophysical modeling is reported here. The calculation and application of cold lanthanide opacities to the study of light curves produced in neutron star mergers (NSMs) is specifically discussed. The astrophysical site of the nucleosynthesis r-process (rapid neutron capture) remains unknown. While the r-process is widely accepted to occur in core-collapse supernovae, it cannot account for the relative abundances of all of the heavy elements in the universe. Therefore, it is of interest to study compact objects with large concentrations of neutrons, such as NSMs, which may provide alternative sites for r-process production. In order to know if/how it is possible to distinguish NSMs from other events, one needs to simulate the light generated by them, which requires the use of heavy-element opacities calculated at cold, low-density conditions. Thus, opacities are presented for lanthanide elements in fine-structure detail and the consequences of these data for the possible detection of NSMs are discussed.

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Spectroscopic Investigations of Implosions on the National Ignition Facility

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Hydrodynamic instabilities are a primary impediment to the success of inertial confinement fusion (ICF), as they can severely degrade capsule performance [1]. Even with perfectly smooth capsules, the fill tube and capsule support provide perturbations that seed instabilities. Consequently, understanding the evolution of perturbations and their effects on capsule performance is critical to the success of an ICF program. We discuss here the use of spectroscopic methods to diagnose the growth of hydrodynamic instabilities in imploding capsules. To understand capsule evolution and guide experimental design and interpretation, we use high-resolution HYDRA [2] simulations, postprocessed with Cretin [3], to simulate the spectra produced by capsules with specified initial perturbations. The spectral simulations cover a wide range of conditions, from the multi-keV hot spot to the cold dense pusher.

For capsules with mid-Z dopants, the resulting X-ray spectrum can be analyzed to obtain information about the plasma conditions. An analysis of the dopant K-shell line emission has been used to estimate the mass of ablator material mixed into the hot spot [4]. Other spectral features can be used to provide information about the shell and further constrain the mixed mass. Other recent work has focused on using spectroscopy to quantitatively characterize the growth of perturbations. Capsules containing a small amount of argon in the gas produce sufficient emission before peak compression to provide radiographic information. The analysis of simulated spectra from capsules with machined perturbations demonstrates the possibility of extracting quantitative measures of perturbation growth.

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Progress in modeling astrophysical plasmas*

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The Universe contains a broad range of plasmas with quite different properties depending on distinct physical processes. In this contribution I will give an overview of the recent developments in modeling such plasmas using the SPEX package developed at SRON. The origin of this package dates back to the early seventies of the last century. I will present recent work on the update of atomic parameters in the code that describes the emission from collisional plasmas, where older approximations are being replaced now by more accurate data. Further I discuss the development of models for photo-ionized plasmas in the context of outflows around supermassive black holes and models for charge transfer that are needed for analyzing the data from the upcoming ASTRO-H satellite.

Detailed Spectra Modeling in Low-Density Plasmas

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The spectral properties of low-density plasmas are generally considered to be much easier to simulate as compared to dense optically-thick plasmas. Indeed, a simple coronal model may often provide accurate description of radiative power losses or spectral emission in strongest electric-dipole lines. However, more subtle spectral features, such as intensities of forbidden lines or spectral patterns under induced electric fields, may require not only a full-scale modeling of all relevant collisional and radiative processes but also development of new methods and tools for spectra calculation and analysis.

This approach will be exemplified by several applications of collisional-radiative (CR) modeling to low-density plasmas of electron beam ion traps (EBITs) and magnetic fusion devices. In particular, we will discuss identification of inner-shell dielectronic resonances from 50+-times ionized tungsten under EBIT conditions [1] and the effect of a magnetic-dipole line on allowed transitions in Kr^{23+} and its potential use for fusion diagnostics [2]. In addition, the results of experimental validation of the recently developed CR parabolic-state model for motional Stark effect using the latest data from the Alcator-C Mod tokamak [3].

Another important subject for modeling applications is single-electron and multielectron charge exchange that is highly important in astrophysics, magnetic fusion, and some other fields of research. Charge exchange is known to provide very distinct spectral features due to electron capture into relatively high shells. While the spectra due to single and double electron transfer can be calculated reasonably well using standard CR models [4], the population kinetics and photon emission following multiple electron capture (MEC) have so far been treated with very approximate qualitative models. Moreover, the number of atomic states to be included increases significantly due to a large number of possible combinations of the electron momenta. We will present a detailed Monte-Carlo stabilization model for MEC that utilizes accurate radiative and autoionization data, can operate with tens of thousands of atomic states, and is orders of magnitude faster than the CR time-dependent simulations.

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From Spectroscopic Diagnostics of Black Hole Winds to Their Physical Structure

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The photo-ionized winds driven by active galactic nuclei (AGN) are mostly studied through absorption lines in their X-ray spectra readily measured by space observatories such as XMM-Newton and Chandra. Since no imaging resolves these sources, all physical inferences need to be spectroscopic. We will demonstrate the rich absorption features of AGN winds that often include all charge states (e.g., neutral to H-like Fe) and show how the observed spectra can be used to interpret the physical structure of the winds.

The talk will describe in detail a recent model of radiation pressure compression of the photo-ionized gas that provides a natural explanation for the observations and has testable predictions for the gas pressure of the wind

Lineshape modeling for collisional-radiative calculations

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Collisional-radiative (CR) modeling is widely used to diagnose laboratory and astrophysical plasmas through fitting and interpreting measured spectra. Analysis of spectral line broadening or, more generally, lineshape analysis is an indispensable tool for plasma diagnostics. It allows for non-intrusively inferring basic plasma properties (density, temperature) and more advanced aspects, such as presence of non-thermal electrons or electric and magnetic fields. The line broadening also affects the radiation transfer and, hence, may influence the level or even charge-state populations for non-optically-thin plasmas. Therefore, failure to include line broadening in a CR model may result in severe degradation of its diagnostics power. However, accurate lineshape calculations are rather time-consuming, which renders including them directly in CR calculations unrealistic.

In my talk, I will discuss computationally effective approximate methods of lineshape modeling that retain a reasonably good accuracy, and present examples of such calculations, including modeling of continuum lowering.

Spectral characterization of pulsed plasma discharges at the Chilean Nuclear Energy Commission (CCHEN) and at the NSF ERC for Extreme Ultraviolet Science and Technology

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Research in pulsed electrical discharges at the Chilean Nuclear Energy Commission (CCHEN) currently focuses in a couple of device types: Plasma Focus discharges and Wire array discharges. Plasma Focus devices available at CCHEN have stored energies that range from 0.1 J (nanofoco) to the hundreds of kilojoules (SPEED 2), which enable the study of a wide range of physical phenomena. This work presents results obtained in PF-400J (176-539 J, 880 nF, 20-35 kV, quarter period ~300 ns). Spectroscopic observations were made by means of a 0.5m Czerny-Turner imaging spectrometer attached to a 20 ns integration time ICCD VIS camera. Spatial resolution was obtained by using a telescopic system that enabled the observation of a small volume of the sheath. Gas impurities (Neon, Nitrogen, Argon, and Krypton) were added in different concentrations (2 and 5%) to the background gas to be able to observe the ionization evolution of the plasma sheath when moving in the inter-electrode space. Ionization degrees up to N V were observed in Nitrogen and up to Kr II/III when Krypton was used. Wire array experiments (X-pinch) with a small current amplitude were carried out in the Multipurpose device (1.2µF, 345J, 47.5nH, T/4=500ns and Z=0.2Ω in short circuit). With a wire load and 24 kV of charging voltage, currents up to 122 kA were observed with a 500 ns quarter period. Spectral observations were done with a 1 m grazing incidence off-Rowland Circle spectrometer. A 4-strip MCP detector allowed the acquisition of spectra at different moments of the current pulse, with a time integration of 10 ns. Aluminum and Copper wires were used in different shots showing the appearance of Cu XVII to Cu XXII at the beginning of the current pulse. Aluminum shows emission from Al V to Al IX ions. Characterization of the X-ray emission with a convex KAP crystal spectrometer from the hot spots generated by these plasmas is underway.

A collaboration with the NSF ERC for Extreme Ultraviolet Science and Technology, Fort Collins, Colorado, USA, enabled the spectroscopic characterization of a pulsed capillary discharge that produces a high degree of ionization of a high aspect ratio (~300:1) plasma column with modest currents and fast risetimes (~40 kA, 4 ns). An alumina capillary of 0.5mm ID, filled with 500 mTorr of Xenon allowed the observation of ionization levels up to Fe-like (Xe28+) Xenon, and a 80:1 H2:Xe mixture enabled the observation of levels up to Cr-like (Xe30+) Xenon. Time-resolved spectra were acquired with a flat field grazing incidence spectrometer attached to a MCP and CCD detector. Higher energy spectra were obtained with a convex crystal spectrometer attached to a CCD detector, integrating over the whole current pulse. Interesting spectroscopic phenomena was observed, in which the intercombination line 1s2 1S0 – 1s2p 3P1 of He-like Aluminum and Silicon presented a higher intensity than the recombination line 1s2 1S0 – 1s2p 1P1. These plasma columns could enable the development of sub-10nm x-ray lasers in Xenon discharges, where spectral transitions of Ni-like Xenon from the 4d to 4p are observed.

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Radiation transport, fluid dynamic and collisional-radiative model of radiative shock waves in H2/He mixture for aerospace and astrophysical plasmas

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We have developed a comprehensive state-to-state (STS) kinetic model, coupling the master equations for internal distributions of heavy species with the Boltzmann equation for the free electrons and the radiative transfer equation (RTE). Local plasma emissivity and absorption coefficient are calculated using an accurate model [1] taking into account bound-bound, bound-free and free-free transitions. Solution of the RTE is performed to determine self-consistent values for the rate coefficients of photoinduced atomic transitions and photoionization [2]. Rate coefficients of electron-impact processes are self-consistently calculated integrating the local non-equilibrium electron energy distribution function over the relevant cross section [3]. A detailed collisional-radiative model (CMR) of a H2, $H2^+$, H, H^+, He, He^+ and e^-plasma, including the most significant radiative, electron impact and heavy particle impact processes, is applied to study the structure of a steady radiative shock created at the impact of an hypersonic vehicle (v=20−50 km/s) with high-temperature Jupiter's atmosphere. Preliminary reåsults concerning the application of this model to extremely low density conditions of relevance in astrophysical shocked flows [4] are also reported.

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Improved Collisional Line Broadening for Low-Temperature Ions and Neutrals in the spectral modeling code ATOMIC

H. M. Johns, D. P. Kilcrease, J. Colgan, E. J. Judge, J. E. Barefield II

The Los Alamos National Laboratory (LANL) spectral modeling code ATOMIC, a part of the LANL suite of atomic physics codes, produces emissivity and opacity calculations for plasmas based on ab-initio atomic data from CATS and ionization cross-sections from GIPPER. It uses this atomic data to solve collisional-radiative atomic kinetics rate equations in either LTE or NLTE for single or multi-element plasmas. The ability to model complex systems with many thousands of lines in a reasonable computational time has required compromises in the treatment of Stark line broadening. The approximate model currently used [1] is based on the assumption that the complete set of all available transitions will contribute to the broadening, yielding a line width based on matrix elements proportional to the effective n, l quantum numbers of the levels of the transition in question and the electron temperature and density of the system. While this has been a reasonable estimate for high temperature systems, for low temperature (~ 1eV) plasmas, this approximation appears to overestimate the amount of broadening. This is because the threshold characterized by the ratio between the transition energy and the temperature of the system is much larger, so that the amount of Stark broadening a given state imparts is strongly correlated to its distance in energy from the transition in question. However, with improvements in computational resources it becomes possible to improve ATOMIC’s treatment of line broadening for low temperature plasmas comprised of neutral atoms and low-charged ions (+1 and +2). For this purpose, we have implemented two collisional line-broadening models based on the impact parameter approximation. For neutral radiators, we utilize a variation of Griem’s semi-empirical model [2]. For ion radiators, we utilize a semi-classical approach incorporating the hyperbolic curvature of the incoming electron’s path [3]. We will compare widths extracted from each model to published experimental line widths for Ca I and Ca II lines [4]. As a real world test, we will model Ca spectra from a low temperature CaF2 plasma produced in laser-induced breakdown spectroscopy (LIBS) experiments. We will compare the results of ATOMIC with and without the new collisional broadening routines against an independent line shape model [5].

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Atomic processes in low-pressure argon afterglows

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Recently Celik et al. [1] presented a comprehensive description of the kinetic processes in a low-pressure noble-gas plasma afterglow. They supported their experimental findings by analytical models but some unknown quantities had to be adjusted by fitting the model predictions to experimental data. Hence, their analysis was, in part, only qualitative. The main obstacle preventing a more quantitative description arose from the complex population dynamics of the excited states of the atoms in a recombination-dominated afterglow.

We have now remedied this problem by constructing a complete collisional-radiative model of recombining noble-gas plasma. It concentrates on the highly excited Rydberg states, which play a dominant role in the electron capture by three-body collisions. The high probability of their reionisation keeps the populations of these high Rydberg states close to Saha equilibrium. This provides a gradual limitation of the states at which the electrons can be effectively captured, in contrast with the sharp cut-off introduced in the previous work.

The collisional-radiative model allows the calculation not only of the net recombination rate but also of a number of other important characteristics. These include, for example, electron heating due to the energy released by recombination as well as the temporal evolution of the excited states, with the metastable atoms being of greatest interest for plasma applications. The model is coupled with the equations for the temporal evolution of the electron density and temperature. This allows a full *ab initio* calculation of the temporal evolution of a number of important plasma characteristics, in particular the electron density and temperature as well as the metastable atom density. The only remaining input parameters for the calculation are the initial values of the quantities, which are taken from the experiment. The calculated and measured temporal evolutions of the various parameters are compared and an excellent quantitative agreement is found throughout. Somewhat surprisingly, it was found that a precise agreement is only possible when the effect of the extensive gas heating is taken into account that was not included in the work of Celic et al. [1].

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Two categories of spectroscopic measurements and analyses for the fusion plasma diagnosis

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The plasma spectroscopy can be categorized into two groups. One is the detailed analysis of a single emission line profile. The Zeeman effect, Stark effect, Doppler broadening, and Stark broadening are the examples of this kind. Each of these effects is directly connected to a certain physical parameter and the measured line profiles can be used to obtain the corresponding parameters. The other category of the plasma spectroscopy focuses on the line intensity distribution of the same charge state ions or atoms. The line intensity distribution stands for the population distribution of excited states. Since the population distribution generally depends on the plasma parameters such as the electron temperature T_e and density n_e, those parameters can be conversely determined by the measured population distribution.

A recent example of the line profile analysis in the Large Helical Device (LHD) is the Balmer-α line measurement [1]. The observed line profile is found to contain a significant broad component and is never fitted with a single Gaussian function, rather it is understandable to regard the line profile as a superposition of different Doppler components which is mathematically expressed as a Laplace transform. A numerical inversion of the Laplace transform of the measured line profile yields the emissivity distribution function with respect to the atom temperature. The temperature dependence of the line emissivity is well translated to the spatial dependence so that the ionization rate and the atom density of neutral hydrogen in the plasma core region are determined. The atom density at the plasma center is found to be six orders of magnitude smaller than the maximum at the plasma boundary.

An example of the line intensity measurement in LHD is the helium line analysis for the T_e and n_e determination [2]. The temporal variation of spectra in the visible range is measured for a discharge in LHD, where nine emission lines of neutral helium are identified in each spectrum. A collisional-radiative (CR) model, which calculates the excited level populations for a given set of T_e and n_e, is called for and a determination of T_e and n_e is attempted so that the CR-model results give the best fit to the measured population distribution. It is found that the obtained parameters vary as the line-averaged n_e by the laser interferometer is increased in the course of a discharge. The comparison of the results with those of Thomson scattering diagnosis shows that the radial position of helium line emission is almost fixed at the location where the connection length of the magnetic field to the divertor plate is increased beyond 10 m. Because intense line emission implies vigorous ionization of atoms, the radial location obtained here can be regarded as an effective boundary of the plasma.

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Experimental determination of the ion temperature and hydromotion in an imploding plasma: Implications for pressure and energy balance

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Distinguishing between ion kinetic energy placed in hydrodynamic motion from thermal motion in plasma is of fundamental significance for laboratory plasma physics, astrophysics, and hydrodynamics, including high energy density (HED) plasmas, where energy placed in hydrodynamic motion contributes neither to radiation nor to fusion reactivity, whereas ion temperature does.

Yet, distinguishing ion temperature from hydromotion in HED plasmas has been regarded to be very difficult, since the Doppler-broadened line shapes of emission lines can be due to either effect. However, two novel spectroscopic methods have been developed and implemented experimentally for this purpose [1, 2].

The first method is based on the rate of heat transfer from ions to electrons. To this end, we measure the total ion kinetic energy and its dissipation rate, the total radiation from the plasma, and the electron density and temperature (both also required for knowing the ion-electron thermalization time).

The second method is based on the effect of the ion-ion coupling on the shape of Stark-broadened lines; this effect depends on the ion temperature. For this method, transitions of moderately-coupled ions should be selected, the electron density should be determined, and the Doppler broadening of the emission line selected should be small.

The experiments were performed using neon-puff z-pinch plasmas. Required were observations of high-resolution in spectrum, space, and time, augmented by line shape and time-dependent CR and radiation-transport modeling.

The ion temperature was discriminated from the hydro-motion, and was found to be significantly lower than the total ion kinetic energy. The dissipation time of the hydromotion was determined.

Diagnostics and analysis of wire-array experiments on the Z machine (Sandia) were also made. The data from the WIS and Z experiments allowed for assessing reliably the pressure and energy balance in the stagnating plasma. This was used to examine a reflected-shock model, giving a good agreement. This gave the stagnation pressure and energy balances, and inference of the current flowing in the plasma, yielding that the effect of the magnetic field at the stagnating plasma on the plasma energy and pressure balance is small [3]. The results have been modeled at NRL USA [4].

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Simultaneous estimations of plasma parameters using quantitative spectroscopy

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The observed spectra from a plasma source is quite rich in information content. Basically, it is combination of effects of electron density, electron temperature, ion temperature, ground state atomic density, ground state ion density, metastable state density, plasma motions, impurity concentrations, etc. A few of these quantities can be measured quite straightforwardly in a separate manner. However, for the simultaneous measurements, accurate knowledge of atomic properties, such as, emitted wavelength, transition probabilities, collisional cross-sections, etc. and also all the processes of populating and depopulating the levels by mean of excitation, de-excitation, spontaneous emission, ionization, recombination from adjacent ionization stages, etc. are highly required. Very recently we have developed a method on the basis of experimentally observed absolute intensities of a number of spectral lines of helium/hydrogen in the visible region to infer large number of plasma parameters simultaneously for laboratory based plasma systems [1-2]. The collisional-radiative (CR) model code of atomic data and analysis structure (ADAS) database has been used for this purpose. With an approximation of optical thin plasma, the electron density, electron temperature, ground-state atom and ion densities and also the triplet metastable state ($2\ {}^3S$) density are the parameters estimated [1]. The derived plasma parameters are then used to theoretically obtain the absolute intensities of a few lines in the vacuum ultraviolet (VUV) region. These have been compared with the observed VUV spectral lines, recorded simultaneously with the visible spectra, using a VUV-spectrometer-detector system for which intensity calibration was not available. This analysis has helped to generate a calibration curve for VUV-spectrometer-detector system. The developed method is much cost-effective in comparison to the commonly known branching ratio method used in Tokamak plasmas [3-4]. It is found that for a penning plasma discharge source the inclusion of opacity in the observed spectral lines through CR-model based photo emission coefficients (PECs) and addition of diffusion of neutrals and metastable state species in the CR-model code improves the electron temperature estimation in the simultaneous measurements [5]. The results of this analysis and the development work of laboratory based VUV-spectrometer-detector system calibration technique [1-2, 5] using penning plasma discharge source [6] will be presented.

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Atomic and Molecular Spectroscopy in the Scrape-Off Layer of High Temperature Fusion Plasmas

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Atomic and molecular spectroscopy in the plasma edge of fusion plasmas gained importance in the last decade. Three principle categories can be distinguished here: (i) impurity spectroscopy to determine sputtering sources of s and extrinsic seeding species strength, (ii) hydrogen spectroscopy to determine the divertor characteristics and recycling fluxes, and (iii) extrinsic impurities used to probe the plasma in a non-pertubative way. Due to the high temperature of the magnetically confined edge plasma, even in the Scrape-Off-Layer, are dissociation and ionisation processes responsible for the destruction of atoms and molecules and only in detached divertor conditions can recombination become prominent. Electron impact excitation from the ground state and radiative decay are the basic processes though for a set of important atomic and molecular species in fusion plasmas (D, C, He) meanwhile collision-radiative models exist which take e.g. level mixing, metastable, cascades etc. into account. The situation is worse for W which is currently the most important impurity due to the first divertor selection in ITER and the abandon of carbon as plasma-facing material PFM.

We present the actual status in deuterium molecular spectroscopy used to determine the composition of the plasma-facing surface with respect to the atomic-to-molecular flux ratio as well as the isotopic composition of the recycling flux. The identification of T_2 and DT Fulcher-band spectroscopy from the JET Tritium Trace Campaign and the high sensitivity to determine the T content of about 0.1% will be shown. Secondly, the hydrocarbon catabolism had been studied extensively in TEXTOR by injection of all types of hydrocarbons $C_x(D,H)_y$ and the footprint of the injected species in the edge plasma measured. Inverse photon efficiencies for spectroscopic detectable molecules (CD, CD^+, C_2) and atoms/ions D, C, C^+, C^{2+} detected and compared with the HYDKIN code. Comparison of the ionic species with ADAS data revealed up to a factor 5 differences in the efficiency which is likely due to direct excitation in higher state and not the electronic ground state. Moreover, the sputtering yields of the newly selected PFMs in ITER: Be and W and associated experiments with the JET-ILW to determine the erosion yield and molecular destruction in the plasma will be presented. Thereby, chemical assisted physical sputtering (CAPS) in JET limited discharges has been identified to be responsible for a fraction of the total be source. The measurement of CAPS was performed via the A-X band of the Bed molecule in the SOL and simultaneous measurement of BeI and BeII whereas BeII includes both types of physical sputtering. Under constant bombardment of D^+ and high fuel content in the interaction layer (supersaturation) is the release mechanism strongly dependent on the surface temperature. The increase of the surface temperature from 570K to about 800K extinguished the channel for CAPS. About 1/3 of the total yield at impact energy of 75eV is caused by CAPS: its contribution rises at lower energies though still an energetic threshold exists. Finally, experiments with WF6 injection are presented which deliver S/XBs-values to calibrate WI photon fluxes from W limiters at TEXTOR and divertor plates at JET. The first documentation of swift chemical sputtering of W via WD is presented.

Estimation of oxygen transport coefficients using the O^{4+} visible spectral line in the Aditya tokamak

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To investigate the oxygen impurity transport in typical discharges of Aditya tokamak, spatial profile of brightness of Be-like oxygen (O^{4+}) spectral line (2p3p $^3D_3$-2p3d $^3F_4$) at 650.024 nm is recorded using a 1.0 *m* multi-track spectrometer (Czerny-Turner) capable of simultaneous measurements from eight lines of sights. The emissivity profile of O^{4+} spectral emission is obtained from the spatial profile of brightness using an Abel-like matrix inversion. The oxygen transport coefficients are then determined by reproducing the experimentally measured emissivity profiles of O^{4+}, using a one-dimensional empirical impurity transport code, STRAHL. After calculating the density profile of each charge state, the emissivity of the particular transition, 2p3p $^3D_3$ - 2p3d $^3F_4$, at 650.024 nm is estimated from $\varepsilon_{z,i,j}(r) = n_{z,i}(r).n_e(r).PEC_{z,i,j}(r)$, where n_z and n_e are the impurity and electron densities and PEC is the photon emissivity coefficient. The PEC values depend on both electron density and temperature and are obtained from database ADAS. Much higher values of diffusion coefficient compared to the neo-classical values are observed in the high and low magnetic field edge regions of typical Aditya Ohmic plasmas. The diffusion coefficients are recalculated using PEC values from NIFS atomic database. The estimated diffusion coefficients using PEC values from both the databases are then compared with those calculated from the fluctuation induce transport. Although similar profiles for diffusion coefficients are obtained using PEC values from both databases, the magnitude differs.

Electron trapping by strong Coulomb coupling in a relativistic laser plasma

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When an ultra-intense laser pulse ($I > 10^{19}$ W/cm2) impinges onto a solid, a hot plasma is formed within the relativistic skin depth of a few tens of nanometers. From here, electrons are accelerated by the laser field to relativistic energies and propagate through the target. These electrons partly reflux, or recirculate, on complex trajectories, while strong electromagnetic fields and return currents build up. A proper understanding of this electron transport in solid-density plasmas is crucial for progress in key applications including laser-driven x-ray sources, which can be used in backlighting, for x-ray Thomson scattering experiments, or can provide alternative radiation sources for both scientific and medical applications. The spatio-temporal electron energy deposition is essential for the quest of laser-accelerated protons and the Fast Ignitor concept in inertial confinement fusion.

We measure the three-dimensional distribution of K□ emitting ions inside a 25 µm Ti foil irradiated by sub-picosecond laser pulses at a relativistic intensity of several 10^{19} W/cm². X-ray spectra with high spectral (E/□E~ 15,000) and spatial (□x ~ 11 µm) resolution are measured at four observation angles. After applying Abel- and Laplace inversion, we derive the time-integrated radial and axial (depth-dependent) K□ yield. Axially, the emissivity decays exponentially towards the target rear side. This axial gradient transitions into a homogeneous emissivity for radii > 45 µm. Our results are in qualitative agreement with particle-in-cell simulations.

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Hot electron production at shock-ignition-relevant conditions characterized by high-resolution x-ray spectroscopy and monochromatic imaging

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Diagnostic applications of x-ray spectroscopy provide comprehensive information on environmental conditions and processes accompanying creation and evolution of moderately or strongly coupled plasmas. Successful exploration of ultradense plasma formations, where x rays offer the most efficient and sometimes the only vehicle capable of providing the desired diagnostic information, requires interlinking of the measured radiative properties with underlying phenomena occurring in the extreme-state matter and application of the well-tested advanced instrumentation suitable for obtaining high quality spectroscopic data. We provide a brief survey of high-resolution spectroscopic methods based on x-ray Bragg diffraction from crystals and define limits of their performance. Benefiting from application of modern spectroscopic approaches, we report experiments aiming at characterization of suprathermal electron production in Cu foils laser-irradiated at shock-ignition-relevant conditions.

Generation of hot electrons accompanying interaction of high-intensity lasers with targets, their transport and energy deposition in the near-solid density matter with a varied degree of ionization represent one of the key issues for realization of alternate schemes of inertial confinement fusion. In a series of experiments being performed at Prague Asterix Laser System PALS, the laser-plasma coupling is studied at intensities up to 5×10^{16} W/cm^2, i.e., at parameters of the laser spike envisaged to launch the shock wave igniting the fusion reaction. The role of hot electrons is ambiguous: they contribute to enhancement of the ablation pressure but they may also preheat the pre-compressed targets. Here we report a novel approach to diagnosis of hot electrons based on a combination of monochromatic x-ray imaging and high-resolution K-shell spectroscopy.

The experimental part of this research was carried out using the PALS iodine laser with the wavelength of 1.315 μm, pulse duration 0.25 ns, and energy of about 400 J focused to a diameter of 100 μm, i.e., massive or thin-foil Cu targets were irradiated at coupling parameter $I\lambda^2 = 3.5\times10^{16}$ W μm^2/cm^2. The 2D-resolved quasi-monochromatic x-ray images of the Cu Kα emission produced by interaction of hot electrons with near-surface copper ions were recorded using the spherically bent crystal of quartz (422) in the normal incidence imaging configuration. The 1D spatially resolved Cu K-shell spectra covering the photon energy range of 7.5-8.5 keV (i.e., Cu He-like to Kα emission) were observed using the x-ray spectrometer equipped with the spherically bent crystal of quartz (223). Based on results of modelling, the recorded spectra were interpreted with respect to the hot electron presence in early stages of the target irradiation. The measured intensity distribution of spectral lines close to Kα emission, particularly $2p\rightarrow1s$ transitions in Ne-like to He-like Cu ions, is of paramount importance for rigorous evaluation of fluorescence cross-sections decisive for quantitative interpretation of 2D images. By combining results of X-ray imaging, high resolution spectroscopy, and Monte-Carlo Penelope code modelling of hot electron penetration and deposition of their energy into low temperature, quasi-solid density target we provide more precise estimates on conversion efficiency of the laser energy into hot electrons.

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Analysis of the X-ray emission from well-characterized, NLTE, mid- and high-Z laser-produced plasmas

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Multicharged ions are present in hot dense plasmas and rule the radiation transport in numerous environments, like stellar atmospheres, or plasmas used for inertial confinement fusion. In the past years, non local-thermodynamic-equilibrium (NLTE) collisional-radiative models, often based on the superconfiguration description of the atomic levels, have widely progressed for the calculation of spectra emitted by multi-charged mid-Z ions but several discrepancies still remain. Benchmarking by well-diagnosed experiments is thus still needed for the validation of such codes. In past years, several experiments have been performed at LULI aiming to validate atomic kinetic codes. We concentrated our efforts to testing and enhancing reliability of hydrodynamic diagnostics, beside spectroscopic diagnostics, to fully characterize the plasma emissive region. The hydrodynamic diagnostics permit to constrain hydro-radiative codes, which can then be used as input data for atomic kinetic codes.

In the experiment described in this talk, we irradiated Nb and Ta dots with the two frequency doubled, 1.5 ns duration beams of the LULI2000 laser facility to reach an intensity on target of about $2 \cdot 10^{14}$ W/cm^2. A conical crystal spectrometer allowed the measurement of the Nb L-shell and Ta M-shell emission, in the 2.5-2.9 keV spectral range. Time-resolved Thomson scattering diagnostics measured the electronic density and temperature, and a rear-face self-emission diagnostic measured the shock speed in the solid. These hydrodynamic measurements have been used to constrain the 1-D MULTI hydro-radiative code. The atomic physics code FLYCHK has then been used as a post-processor of the hydrodynamic code, to reproduce the experimental X-ray spectra. We have also performed more sophisticated 2-D hydro-radiative simulations with the FCI2 code, showing a global coherence with the measured data with no need of laser parameter adjustment. NLTE spectra calculations with the atomic physics code AVERROES have also been realized to have deeper insight in the experimental measurements. The results of these analyses will be presented.

Atomic processes in dense plasmas

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In recent years, new regimes of matter have been created with large plasma generation devices, such as NIF (National Ignition Facility), high power short pulse lasers, X-ray free electron lasers (XFEL) and Z machines. New states of matter have been created over a wide range of plasma conditions: hotter and denser, highly transient, warm dense, or astronomically high x-ray photoionized plasmas. The new state of matter requires new theories and modelling capabilities. In terms of diagnostics, plasma spectroscopy has been applied to understand the new states of matter.

To address the issues in plasma spectroscopy of the new state of plasmas, a generalized model of atomic processes in plasmas, FLYCHK, has been developed over a decade to provide experimentalists fast and simple but reasonable predictions of atomic properties of plasmas. For a given plasma condition, it provides charge state distributions and spectroscopic properties, which have been extensively used for experimental design and data analysis. It has been applied to a wide range of plasma conditions relevant to long or short-pulse laser-produced plasmas, tokamak plasmas, or astrophysical plasmas. The FLYCHK code is currently available through NIST web site (http://nlte.nist.gov/FLY) for more than 600 users.

An overview of new machines used by high energy density physics will be given, and the FLYCHK code descriptions and applications are presented.

Role of line emission spectroscopy in the understanding of the divertorphysics of magnetic fusion devices

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The community of scientists involved in magnetic fusion research admits that the divertors ofstellarators and tokamaks allow the achievement of high plasma performances in terms of confinement and power. Divertor plasmas can be at different regimes from ionizing to recombining. Ionizing regimes correspond to plasma parameters of about ne=1019 m-3 and Te=10-100 eV and lead to attached divertor plasmas. Recombining ones are reached at lower temperatures Te=1-3 eV and higher densities ne=1020-1021 m-3 and lead to detached plasmas [1]. Moreover, according to the divertor target and the wall materials, various species of impurities at different ionization stages can be found in addition to hydrogen (and/or its isotope) neutrals, molecules and ions. Therefore, the accurate characterization of divertor plasmas is a major issue as they strongly affect the performances of the confined plasma. For such a purpose, line emission spectroscopy is a method of choice. It is even the unique technique to characterize detached plasmas for which probe measurements are not reliable. We propose to review the different spectroscopic techniques based on line intensities, line profiles or on both of them for conditions relevant to divertor plasmas at ionizing and recombining regimes with numerous illustrations through concrete comparisons of calculations with experimental measurements from various devices. Illustrations concern for instance the use of high members of the Balmer series of hydrogen in detached plasmas of JET [2], the use of the Hα emission in attached plasmas of Tore-Supra to get valuable information on the velocity distribution functions of the neutrals [3]. Another important illustration concerns the analysis of the carbon emission from a detached plasma divertor of JT-60U in the presence of an X-point MARFE [4-5].

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Current needs and developments in X-Ray Crystal Spectroscopy for ITER

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X-ray Crystal Spectroscopy (XRCS) of Hydrogen or Helium like ions of low or medium Z impurities in the plasmas is of significant importance in the nearly 45 planned diagnostics for ITER [1]. The XRCS-Survey [2], a broad-band Bragg spectrometer, is one of the first diagnostic systems which will be put in the group of diagnostics on ITER helping the start-up of the plasma operations. The primary function of this spectrometer will be to accurately measure plasma impurity concentration and their in-flux at ~10 ms intervals in order to reliably operate the machine during all phases of the ITER operations. For profile measurements of important plasma parameters, high-resolution spectroscopy is performed for core [3] and edge plasma through an equatorial port and an upper port of ITER respectively. The XRCS-Edge, a modified Johann spectrometer, is dedicated to measure profiles of ion temperature and poloidal rotation velocity in the plasma edge regions. This spectrometer is mainly required for advanced plasma control and will provide valuable data for edge pedestal physic. These spectrometer systems will have to reliably function in the high radiation environment of the ITER.

The XRCS-Survey and Edge spectrometers are in detailed design phase to meet the ITER requirements. Preliminary performance has been simulated with the impurity emission data modelled with ADAS atomic database and SANCO impurity transport code. The talk will focus on the current design challenges and ongoing developments of X-ray crystal spectroscopy for ITER edge diagnostics and impurity survey including further advances needed in the applicable technology.

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Assembling atomic data for diagnosing and modelling fusion plasmas

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Modern spectroscopy techniques for diagnosing magnetically confined fusion plasmas, and the linked topic of modelling the impurity transport, demand high quality atomic data. The fundamental atomic quantities, such as energy levels and excitation rates, are not sufficient in themselves to describe the behaviour of radiation in finite-density plasmas. Effective coefficients, derived from a collisional-radiative population model, are the appropriate quantities to use [1].

The wide variety of elements present in fusion and astrophysical plasmas means that coverage across the periodic table is also a requirement for the provision of atomic data. Impurity transport modelling and radiated power evaluation requires atomic data for all ionisation stages of an element, rather than iso-electronic collections which are more convenient for large scale computation. With increasing Z, and noting that tungsten (Z=74) is a plasma facing component in current and future machines, the complexity of the emission increases. Therefore methods of handling different resolutions of atomic data, considering spectral features rather than individual lines and incorporating fundamental data with very different uncertainty measures into a coherent model for an element are the current challenges.

Precision spectroscopy will highlight physical processes such as charge exchange from thermal and high energy neutral beams, non-Maxwellian electron distributions, effects on excited populations due to optically thick plasmas and the influence of ion impact as a significant re-distributing mechanism.

ADAS, the Atomic Data and Analysis System [2], is a systematic approach to data provision for fusion studies. There is a database of fundamental and derived data, a set of interconnected codes for generating and processing the data and code libraries for extracting and using the data.

This talk will describe the atomic models within ADAS, the organization of the data and its use. Examples from analysing emission from present day tokamaks, soft X-ray emission predictions for ITER diagnostic design and estimations of radiated power for DEMO will illustrate the breadth of the atomic data need. Methods for assessing the quality of the data, and incorporating this uncertainty into the models, are explored.

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A review of astrophysically motivated atomic recombination and ionization measurements in ion storage rings

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Our understanding of the Cosmos rests, in part, on knowledge of the underlying processes that drive the Universe. Of particular importance for many astrophysical objects are those atomic processes which control the charge state distribution (CSD) of the observed plasmas. The CSD is intimately tied in to the observed spectral features and can also affect the thermal structure of the gas. Accurate atomic data are required in order to generate the CSD calculations necessary to reliably model and interpret astrophysical spectral observations (e.g., [1]).

Cosmic atomic plasmas can be divided into two broad classes: photoionized and electron ionized. Photoionized plasmas are formed in objects such as planetary nebulae, H II regions, X-ray binaries, and active galactic nuclei [2,3]. Electron-ionized plasmas are formed in objects such as the Sun and other stars, supernova remnants, galaxies, and the intercluster medium in clusters of galaxies [4]. In photoionized gas, the CSD is determined from ionization by both photons and the resulting photo-electrons balanced with recombination primarily via low temperature dielectronic recombination (DR). In electron-ionized gas the CSD results from the balance between electron impact ionization (EII) and recombination primarily via high temperature DR.

Here we present some of the various astrophysical motivations behind this research, review examples of relevant DR and EII studies which have been performed on ion storage rings [5,6,7], and discuss some of the implications of the results for both astrophysics and atomic physics.

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Steps Towards Uncertainty Assessment for Calculated Atomic and Molecular Data

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The Atomic and Molecular Data Unit at IAEA is responsible for databases in the area of atomic and molecular processes (and plasma-material interaction processes too) for nuclear fusion. The Unit encourages data development primarily through the mechanism of IAEA coordinated research projects (CRP) and among our recent CRPs has been one on processes of light elements in fusion plasma, one on collisional and radiative processes of tungsten ions and one on atomic and molecular processes of hydrogen and helium. We aim to provide evaluated and recommended data and this in turn requires an assessment of uncertainties in the data. Cross sections and rates for state-resolved collision processes are almost always calculated and therefore the community is faced with the problem of obtaining uncertainty estimates for calculated scattering data [1].

In the present contribution we look at the problem of uncertainty estimates for calculated atomic scattering data in the context of other areas of scientific computing where uncertainties are being studied. On one side of the spectrum lies the established science of numerical analysis, where one deals with precisely specified problems and one develops a theory of discretization error and rounding error. On another side of the spectrum lies the emerging science of Uncertainty Quantification (UQ) for simulation of complex systems [2]; generally systems for which the basic equations are not well established, involve poorly known parameters and functional dependencies, include stochastic elements and give rise to chaotic behavior. A mathematical core of UQ, polynomial chaos, is concerned with uncertainty propagation for dynamical systems.

Atomic and molecular scattering processes occupy their own territory different from numerical analysis and from complex systems. Atoms and small molecules are not complex systems, but they are computationally hard because their description relies on many-body quantum mechanics. For these simple physical systems that are of high computational complexity a new science of uncertainty assessment needs to be developed, or at least a new branch of the developing science of UQ. We discuss possible approaches including the Unified Monte Carlo (UMC) method [3] to estimate uncertainties and their correlation structure. We also note rigorous lower-bound methods for electronic structure and their possible role in uncertainty estimation.

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Poster Presentations

Calculations of Ionization Timescales in a Laser-irradiated Plasma

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Calculations of plasma emission and ionization may be simplified by assuming Local Thermodynamic Equilibrium (LTE), where populations are given by the Saha-Boltzmann equation. LTE can be achieved at high densities when collisional processes are much more significant than radiative processes, but may not be valid if plasma conditions change rapidly. A collisional-radiative model has been used to calculate the times taken by carbon and iron plasmas to reach LTE at varying densities and heating rates. This work shows regimes in rapidly changing plasmas, such as those created by optical lasers and FELs, where the use of LTE is justified, because timescales for plasma changes are significantly longer than the times needed to achieve an LTE ionization balance.

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Spectral characterization of pulsed plasma discharges at the Chilean Nuclear Energy Commission (CCHEN)

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Research in pulsed electrical discharges at the Chilean Nuclear Energy Commission (CCHEN) currently focuses in a couple of device types: Plasma Focus discharges and Wire array discharges. Plasma Focus devices available at CCHEN have stored energies that range from 0.1 J (nanofoco) to the hundreds of kilojoules (SPEED 2), which enable the study of a wide range of physical phenomena. This work presents results obtained in PF-400J (176-539 J, 880 nF, 20-35 kV, quarter period ~300 ns) [1] and PF-2kJ (1.6-3.6 kJ, 8000nF, 20-30 kV, ~ 960 ns time to peak current, dI/dt~ 2.7×1011A/s) discharges. Spectroscopic observations were made by means of a 0.5m Czerny-Turner imaging spectrometer attached to a 20 ns integration time ICCD VIS camera. Spatial resolution was obtained by using a telescopic system that enabled the observation of a small volume of the sheath. Gas impurities (Neon, Nitrogen, Argon, and Krypton) were added in different concentrations (2 and 5%) to the background gas to be able to observe the ionization evolution of the plasma sheath when moving in the inter-electrode space. Ionization degrees up to N V were observed in Nitrogen and up to Kr II/III when Krypton was used.

Wire array experiments (X-pinch) with a small current amplitude were carried out in the Multipurpose device (1.2µF, 345J, 47.5nH, T/4=500ns and Z=0.2Ω in short circuit). With a wire load and 24 kV of charging voltage, currents up to 122 kA were observed with a 500 ns quarter period. Spectral observations were done with a 1 m grazing incidence off-Rowland Circle spectrometer, were light emitted from the discharge was focused into the entrance slit with an adjustable curvature grazing incidence cylindrical mirror. A 4-strip MCP detector allowed the acquisition of spectra at different moments of the current pulse, with a time integration of 10 ns. Aluminum and Copper wires were used in different shots, enabling the observation of the ionization degree evolution from the plasma during the current pulse progression. Preliminary results show the appearance of Cu XVII to Cu XXII at the beginning of the current pulse. Aluminum shows emission from Al V to Al IX ions. Characterization of the X-ray emission with a convex KAP crystal spectrometer from the hot spots generated by these plasmas is underway.

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Spectroscopic observations of homogenous microcapillary plasma columns heated by ultrafast current pulses*

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Homogeneous plasma columns with ionization levels typical of MA discharges were created by rapidly heating gas-filled 520-μm-diameter channels with ns rise time current pulses of only 40 kA [1]. These current pulses allow the generation of unique experimental conditions, producing large aspect ratio (>300:1 length-to-diameter) plasma columns capable of ionizing pure Xenon up to Ni-like levels Xe28+ and Xenon impurities to levels up to the Zn-like state, Xe30+. The use of Neon as the discharge gas enabled the ionization of Aluminum and Silicon (from injected SiH4) to levels up to H-like and He-like. Axially acquired spectra show the unusual dominance of the intercombination line over the resonance line of He-like Al by nearly an order of magnitude, caused by differences in opacities in the axial and radial directions. These plasma columns could enable the development of sub-10nm x-ray lasers in Xenon discharges, where spectral transitions of Ni-like Xenon from the 3d94d (3/2, 3/2)J=0 to the 3d94p(5/2, 3/2)J=1 and to 3d94p(3/2, 1/2)J=1 are observed.

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Plasma imaging and spectroscopic studies from laser-assisted vacuum-arc source

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Laser and discharge produced plasmas are the most extensively studied candidates to produce Extreme Ultraviolet (EUV) light that has to meet strict requirements of high power & brightness among others for applications in micro-lithography for next generation chip production. The hybrid laser-assisted vacuum-arc discharge sources combine the scalability and stability features besides high energy conversion efficiency (CE) of the input energy which has been demonstrated in this report. Time resolved visible imaging and EUV spectroscopy combined with temporal profiles were used to diagnose the EUV photons from laser triggered discharge plasma formed from liquid Sn coated on rotating-wheel-electrodes. The EUV output was found to correlate with the localized ablation of the thin film. This was studied by tailoring laser parameters, mainly the pulse duration and energy density, using two Nd:YAG lasers of ~170ps and ~7ns, each 1064nm, with energy range of ~1-100 mJ. The picosecond (ps)-laser showed an increase in CE and spectral purity compared to ns-triggering. The difference is mainly due to the expanding plasma dynamics.

Observation of Emission of Fast Atoms in the Linear Magnetized Plasma Device PSI-2

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Fast atoms or “hyperthermal atoms” have been observed and discussed in various types of plasmas, such as fusion plasmas, rf plasmas and atmospheric plasmas [1-5]. In this work we present experimental observations of a population of hyperthermal hydrogen (deuterium) atoms in the low temperature plasma (~2-15eV) of the linear magnetized plasma device PSI-2. The plasma ends on a tungsten target which can be biased down to -300V to accelerate positive ions. Optical emission spectroscopy is employed to measure the emission lines D_α, D_β and D_γ. A spectrometer (~0.01Å/pixel) is used to study details of the line shape (energy distribution, Doppler shift). The spatial dependence (||B) of light emission of fast atoms is measured by a 2D spectrometer (~0.1Å/pixel) with the plasma in front of the target being imaged onto the entrance slit. Line broadening in form of wings surrounding the cold component is observed for D_α, D_β and D_γ indicating fast neutral atoms in the energy range of ~100eV. The light emission of fast atoms arises close to the target surface and decays with distance from the target in the plasma column. The population of fast neutral excited atoms varies with bias potential and gas pressure and is pronouncedly present in hydrogen argon mix plasmas. When hydrogen is mixed with krypton, xenon or neon, the population density of fast neutral excited hydrogen atoms is strongly reduced. For helium and pure hydrogen the population could not be distinctly observed above noise level. We discuss the excitation transfer between metastable noble gas atoms and ground states of atomic hydrogen as the driving mechanism for the observed light emission. In case of argon this process is quasi-resonant. Hyperthermal neutral atoms may be usually present in hydrogen and hydrogen mixture plasmas, but for most discharge conditions and gas mixtures fast neutral hydrogen atoms are in the ground state and not visible. The observed effect provides access to the measurement of the angular and energy distribution of reflected hydrogen.

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CXRS Diagnostics on MAST

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Charge eXchange Recombination Spectroscopy (CXRS) is a well-known, mature diagnostic used on many fusion devices. It is used primarily for measuring ion density, temperature and velocity profiles on fusion plasmas [1-4]. Injected neutral beam atoms undergo CX with the bulk plasma ions providing a source of excited C^{5+} impurity atoms. The Doppler shift and broadening of the excited spectral lines can be used to calculate the velocity and temperature profiles respectively. The MAST system has 60 spatial viewing chords with ~1cm spatial resolution. CXRS measurements can in principle measure all the required parameters for calculating force balance through the radial electric field. These calculations have been applied to plasmas with Resonant Magnetic Perturbations (RMPs) for the purpose of studying ELM mitigation [5]. CXRS measurements have shown that the radial electric field well decreases for increasing RMP intensity. These measurements are consistent with measurements on other devices, such as ASDEX and NSTX.

In addition, a thermal He gas puff diagnostic has been implemented with the aim of measuring radial electric fields in the pedestal region [6-9]. The emission region is localised to the pedestal due to poor plasma penetration of low temperature thermal neutrals. The system has 64 spatial viewing chords with 1.5mm spatial resolution. The system is currently configured to observe the singly ionized HeII $(4 \rightarrow 3)$ $\lambda = 468.57$nm line. The hardware configuration of the diagnostic will be described.

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Identification of EUV spectral lines of highly charged tungsten from Zr-like W^{34+} to Se-like W^{40+} ions observed with an EBIT at NIST*

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In recent years, tungsten has drawn much attention in plasma physics because of its high melting point and low erosion characteristic. It is being planned for use as a plasma facing material in the divertor region of the fusion reactor ITER. Because of its large number of orbital electrons, there are many different possible tungsten ions present in the plasma as an impurity. So, spectra observed from the plasma will contain many strong lines coming from these different tungsten ions. The identification of such spectral lines and their intensity ratios can be used to diagnose the different plasma parameters. The intermediate charge states of tungsten i.e. Zr-like W^{34+}- Se-like W^{40+} are among the most prominent ions in the plasma and they radiate spectra in the EUV range. Thus, they play an important role in the radiative losses of the plasma. Utter et al. [1] used the Livermore EBIT to record spectra of Rb-like W^{37+} to Cu-like W^{45+} at beam energies of 1.79 keV to 3.02 keV and in the wavelength region

4.0 nm-8.5 nm. Wavelength and line intensity ratios were calculated using simulated spectra based on the wavelength predictions of Fournier [2].

In the present work, we observed emission spectra from 2.7 nm to the longer wavelength side i.e. upto 17.3 nm for these Zr-like W^{34+} - Se-like W^{40+} ions produced in the EBIT at NIST [3]. Beam energies varied between 1.65 keV and 2.00 keV. The spectral line intensities were determined by performing simulations with the non-Maxwellian CR code NOMAD [4]. The identified strong lines represent electric dipole n = 4-4 transitions in these ions. The radiative and collisional data used in NOMAD were calculated with the FAC [5] code in which the relativistic Dirac equation with a model potential and relativistic distorted-wave approximation for collisional processes are implemented. Good quantitative agreement was found for the wavelengths as well as intensities between the modelled and experimental spectra. 18 new lines were identified among the total 40 lines observed. Our measurements not only added new spectral lines in the region 4 nm-8.5 nm to those reported by Utter et al. [1] but also predicted new lines in the longer wavelength region.

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Suppression and excitation of MHD activity with an electrically polarized electrode at ADITYA tokamak plasma edge

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In ADITYA tokamak biased electrode experiments are carried out to study L-H transition and mitigate deliberately induced disruptions [1]. In these experiments a positively biased molybdenum electrode is introduced from top of the machine to induce high radial electric field and its shear [2]. It is observed in repeatable plasma discharges that at the onset of biasing MHD activity is reduced due to stabilization of m/n = 3/1 mode. In this regime radial profile of plasma current density flattens and particle confinement improves and Hα line radiation is reduced. Later on, during biasing second regime of improved confinement is spontaneously achieved with suppressed electrostatic fluctuations and high MHD activity due to growth in m/n = 2/1 island width, which is caused by steepening of current density radial profile. In this improved confinement regime Hα line intensity increases.

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Visible M1 transition of the ground state and CRM of W^{26+} - W^{28+} ions

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Tungsten (W) is one of the major candidates for divertor or wall material in the next generation magnetic confinement fusion reactors due to its favorable properties. Tungsten atoms will be introduced into plasmas and they will act as impurity ions. Although the heavy ion impurities may cause a serious radiation power loss, their visible line emissions may still helpful for diagnostics of the core and edge plasmas owing to their low opacities[1]. Accurate atomic data of energy levels and transition properties relevant for such line emission are indispensable for the precise measurement of plasma properties. In the present work, we carry out an elaborate non-empirical theoretical calculation for the electronic structures and the M1 transition properties of W^{26+} to W^{28+} ions as well as a simple CRM for EBIT plasma was developed.

Multi-configuration Dirac-Fock (MCDF) method is a widely used ab-initio method to carry out a relativistic calculation for many electron atoms or ions. The effect of electron correlations can properly be evaluated by choosing a suitable set of basis which consists of the orbitals and excitations among those orbitals. We employ the GRASP code for our present calculation[2,3]. We have carried out an MCDF calculation for the ground state multiplets of W^{26+} and W^{27+} ions[4,5] and the first excited state of W^{28+} ions. The Breit interaction was estimated in low frequency limits and the vacuum polarization effect was evaluated by perturbation. In the framework of a restricted active space (RAS) on the MCDF procedure, the visible M1 transitions of W26+ to W28+ have been calculated. We have obtained a good agreement with experiment in Tokyo-EBIT[4] and Shanghai permanent magnet EBIT[5] . The disagreement of the theory with the experiment is only about 0.03eV, which is about 1% of the experimental transition energy.

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Collisional radiative model for the diagnostics of ICP Krypton plasma using relativistic fine-structure cross-sections

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In the present work, the radially-averaged emission intensities in the 750-900 nm range were recorded for low pressure inductively coupled (ICP) krypton plasma in the range of pressure from 1-50 mTorr. A CR model [1] has been developed to study ICP Kr plasma. The various processes such as electron-impact excitation, ionization and their inverse processes through detailed balance principle have been considered. We have calculated fine-structure relativistic-distorted wave (RDW) electron impact excitation cross sections [2] and incorporated in the CR model. The required rate coefficients are obtained by assuming a Maxwellian distribution. Electron temperature is estimated by the best fit between the optical emission measurements for nine strong lines arising from Kr ($4p^5 5p \rightarrow 4p^5 5s$)

transitions and model predications. Results of our calculations along with theoretical details will be presented.

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Hydrodynamics and X-ray emission from tampered copper foils irradiated by kJ-laser

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We have studied the plasma expansion at tampered copper targets by means of high-resolution space resolved X-ray spectroscopy near 8 keV. Two X-ray spectrometers equipped with identical spherically bent quartz Bragg crystals covered the whole spectral interval from the Cu He-alpha until the K-alpha transitions. The plasma emission was simultaneously observed at two line of sights corresponding to 0° and 57° relative to the target surface. The first configuration provided spatial resolution in z-direction (normal to the target surface, i.e., in the direction of the laser propagation) whereas the second spectrometer recorded the spectra with a mixture of spatial resolution along and perpendicular to the target surface. Copper foil targets of different thickness (1.5 μm, 3 μm and 6 μm) have been irradiated with the kJ laser PALS at 1 ω (λ=1. 315 μm), pulse duration of τ = 350 ps and energies of about 500 J.

We have identified irradiation conditions at which i) both spectrometers provide almost identical spectral distribution and ii) significant differences appear in intensities emitted from different charge states between Cu II and Cu XIX. In particular, the spectral region near K-alpha emission shows characteristic variation if tampered targets are used whereas the spectral features near He-alpha turns out to be less sensitive. First interpretation of observed data based on hydrodynamic simulations and atomic physics analysis will be presented.

X and XUV opacity measurements in dense plasmas

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We present the recent experimental work at the LULI-2000 facility about X and XUV opacity measurements in mid-Z laser produced plasma. The aim of this work was, first, to simultaneously measure absorption structures in X and XUV range using different approaches to estimate the plasma temperature and validate the atomic physic codes, and second, to implement a new target design. We were interested in plasma conditions characterized by temperatures between 20eV and 25eV and densities of the order of magnitude of 10^{-3}g/cm^3 to 10^{-2}g/cm^3. We sought to investigate the Ni, Fe and Cu 2p-3d x-ray absorption structures as well as the 1s-2p transition of an additional aluminium layer to confirm the in-situ temperature. Under these conditions in medium-Z plasma the Planck and Rosseland average opacities are often dominated by XUV $\Delta n=0$ ($n=3$) transitions. And the strength of these structures is highly sensitive to plasma temperature.

The experimental scheme was based on two different target designs. The first one was a thin foil of main material, inserted between two gold cavities that were heated by two nanosecond doubled-frequency 300J beams. The plasma was probed by an x-ray backlighter created by a third nanosecond beam with an energy E~20J. This x-ray source was along the axis defined by the two cavities and the foil. In the second set-up, designed to reduce the effect of the Hohlraum self-emission, the two cavities were perpendicular to the radiography axis. For these two schemes, the temperature gradient inside the sample was reduced during the spectroscopic measurement because of both-side irradiation of the foil by the cavities.

In addition to the main spectrometer, several other diagnostics were used. An independent measurement of the radiative temperature of each cavity was performed with a broad-band spectrometer. The x-ray source was measured by two time-integrated spectrometer with different spectral resolution and different viewing angle. Finally a pinhole camera was placed to observe the x-ray emission of the cavities and the backlighting source.

The association of all these diagnostics allowed us to better characterize the sample and constrain the opacity data.

Single pulse laser-induced breakdown on the target in water

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Laser induced breakdown spectroscopy (LIBS) currently represents the only choice for direct elemental analysis of bulk liquids and submerged targets [1]. In order to have precise and reliable LIBS analysis, thorough understanding of laser induced breakdown (LIB) in water, or any other liquid is needed. That has proven to be very challenging, both for theoretical and experimental investigations, due to many factors influencing the process.

In this work, complex phenomena that arise during single pulse LIB on submerged solid target in the distilled water are studied by different experimental techniques, fast schlieren and shadow photography, optical emission spectroscopy and transmission and scattering measurements . Nd:YAG laser source operated at 1064 nm, with 20 ns pulse duration and 50 mJ energy was used for the plasma initiation. Laser beam was focused using two lenses, where the second lens was built in the chamber wall directly. Lenses were aligned in the manner that the laser beam induces breakdown on the surface of solid target placed perpendicularly to the laser beam and vertically inside a chamber filled with distilled water. Chamber was equipped with two quartz windows mounted on the opposite chamber walls. Target was placed in the target holder and translated after each laser shot.

Transmission and scattering measurements were performed under illumination of HeNe laser and green diode laser, respectively. Photomultiplier tube (PMT) with interferential filter (IF) for corresponding illumination was used for signal detection.

In the case of shadowgraphy and schlieren imaging, area above the target surface was illuminated with the white light source. Illuminated area above the sample was further imaged with the lens placed after the chamber exit window. Final image was formed using objective lens mounted on the iCCD camera. To perform schlieren imaging additional vertically mounted knife-edge was positioned in the focus of the lens to monitor refractive index gradients perpendicular to the sample.

For spectroscopic measurements 1:1 image of the plasma plume was projected, by means of optical mirrors, on the entrance slit (100 μm width) of the 0.5-m Ebert-type spectrometer with the grating of 1180 grooves/mm. The plasma radiation was recorded with the ICCD detector mounted on the exit slit plane of the spectrometer. The ICCD was operated by a pulse generator (DG-535, Stanford Research Systems), allowing the choice of gate width and delay time after the laser pulse for the time resolved data acquisition.

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Spectroscopy of a nitrogen capillary discharge plasma aimed at a recombination pumped X-ray laser

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The recombination pumping scheme for soft X-Ray lasers has better energy scaling, than the collisional-excitation pumping scheme. Implementation of an H-like $3 \rightarrow 2$ Nitrogen recombination laser, at λ~13.4nm requires initial conditions of at least 50% fully stripped Nitrogen, kTe~140eV and electron density of ~10^{20}cm^{-3}. In order to reach population inversion, the plasma cooling to below 60eV should be faster than the typical three-body recombination time. The goal of this study is achieving the required plasma conditions using a capillary discharge z-pinch apparatus. The experimental setup includes a 90mm alumina capillary coupled to a pulsed power generator of ~60 kA peak current, with a rise time of ~60ns.

Various diagnostic techniques are applied to measure the plasma conditions, including X-Ray diode, time-resolved pinhole imaging and time-resolved spectroscopy analysed with a multi-ion collisional-radiative atomic model. For optimization of the plasma conditions, experiments were carried out in different capillary radii and different initial N pressures. The results show a fast cooling rate to below 60eV, demonstrating the feasibility of capillary discharge lasers.

Modeling non local thermodynamic equilibrium plasma using the Flexible Atomic Code data

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We developed a new code, Radiative-Collisional code based on FAC (abbreviated RCF), which is used to simulate steady-state plasmas under non local thermodynamic equilibrium condition, especially photoionization dominated plasmas. RCF takes almost all of the radiative and collisional atomic processes into rate equation to interpret the plasmas systematically. The Flexible Atomic Code (FAC) supplies all the atomic data RCF needed, which insures calculating completeness and consistency of atomic data. With four input parameters relating to the radiation source and target plasma, RCF calculates the population of levels and charge states, as well as potentially emission spectrum.

In preliminary application [1], RCF successfully reproduces the results of a photoionization experiment at Sandia National Laboratory Z-facility [2] with reliable atomic data. The effects of the most important atomic processes on the charge state distribution are also discussed. In the calculations of RCF, the charge state distribution of this experiment is a composite result of different atomic processes. The external field dominates the ionizations in the plasma by photoionization directly and photoexcitation plus autoionization indirectly. The transitions within any given single charge state can significantly affect the charge state distribution, and one of the interesting results of our computations is the role played by collisional excitation in this experiment, in which it reduces the total ionization rate by competing with photoionization and photoexcitation.

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Comparison of Transient Plasmas Produced by Nanosecond Laser Pulses and Hypervelocity Impact via Time-Resolved Emission Spectroscopy

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In this work the dynamics of impact plasmas is compared to plasmas generated by nanosecond laser pulses. Impact plasmas are formed during the collision of objects in the velocity range of several kilometers per second which is relevant for aerospace applications. While the laser produced plasmas were widely explored in the past, the knowledge about the dynamics of impact plasmas is less comprehensive. Experiments investigating the impact plasma are carried out using a two stage light gas accelerator, while laser produced plasmas are generated by a nanosecond laser with a pulse duration of 15 ns and a pulse energy of up to 400 mJ. Time resolved spectroscopy is used to determine plasma parameters. With a measurement system consisting of spectrograph and streak camera, the emission spectra of plasma with a lifetime of a few microseconds is recorded time resolved.

For the evaluation of the experimental data, a model was developed to determine relevant plasma parameters like electron density and electron temperature. During expansion plasma conditions are changing from optically thick to optically thin and therefore a noticeable change in spectral characteristic is observable. To obtain plasma parameter for optical thick plasma the radiative transfer is included and a spectrum depending on the electron density and temperature is simulated. For optically thin plasma electron density and electron temperature are determined from the line width and the ratio of line to continuum radiation. The dynamics of laser produced plasma and impact plasma are compared.

Determination of the metastable and resonance excited atomic states populations in CCP Ar discharge using OES techniques.

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In this work populations of the first two metastable and first two resonant atomic states in CCP Ar discharge have been measured using two independent optical emission methods. The first method is based on the comparison of radiation self-absorption effects for plasmas with two different effective sizes. The second method is based on the measurements of intensities ratios of certain lines which are sensitive to plasma parameters. It was shown, that the first method is preferable to use. The dependences of levels' populations on the different plasma parameters were obtained. In particular, it was shown, that the resonant state populations increase with increasing applied power, simultaneously the metastable state populations remain constant. For description of such populations' behaviors the collisional radiative model, containing the first 14 exited atomic states in Ar, has been built. Using this model we also obtain electron concentration and the electron energy distribution function (EEDF), which came out to be non-Maxwellian.

Investigations of plasma parameters and features of compression zone formation in MPC facility using the optical and spectroscopic methods of diagnostics

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The investigations of dense compressive plasma streams, generated by magnetoplasma compressors (MPC), are the important fundamental and application problem [1]. MPC-device which situated in Kharkov (Ukraine) was developed and constructed as source of intensive electromagnetic and corpuscular radiation pulses, and able successfully work at gases with different masses so as with their mixes.

The main attention focused at the studying of the formation and dynamics of the compression zone so as plasma stream characteristics, using optical and spectroscopic diagnostics. In particular, the time of originating and existences of this zone was analysed, so as the temporal behaviour of plasma electron density and other important parameters and characteristics.

Argon was used as the working gas. Several series of experiments with different initial (residual) gas pressure in vacuum chamber were carried out for receiving the optimal plasma parameters. Experiments were carried out in MPC [2] with discharge current of 380 kA and working voltage 20 kV.

In present investigations temporal and spatial distributions of plasma density were measured in plasma stream and compression region for different initial conditions. Quadratic Stark broadening of corresponding spectral lines of argon were used for plasma density calculations. Stark broadening was estimated from full experimental widths taking into account instrumental and Doppler broadening [3, 4]. Plasma dynamics parameters and their distributions were also discussed.

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Diagnostics of Helium plasma by using optical line intensity ratio method

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Electron temperature (Te) and electron density (ne) of He plasma with Te < 10eV and ne < 10^{14} cm^{-3} which was generated in our own small scale plasma discharge chamber, were diagnosed by optical line intensity ratio method. Emission spectrum of neutral He was observed by Czerny-Tuner monochromator which was calibrated with the tungsten halogen lamp. The transition lines of 3^1D-2^1P (667.8nm), 3^3S-2^3P (706.5nm), and 3^1S-2^1P (728.1nm) of He I were selected to diagnose the T_e and n_e of He plasma. The excited states populations for the emission line intensity ratio were calculated by a collisional radiative model [1] for given T_e and n_e. The diagnosed plasma parameters (T_e and n_e) were compared with those measured by using single electric probe.

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Design and Simulation of Cu Target X-ray Source for ITER X-ray crystal spectrometers

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In ITER [1], X-ray Crystal Spectrometer diagnostic is required to provide accurate measurements of real time plasma behaviour and impurity characteristics. At IN-DA, two X-ray crystal spectrometer systems for Edge and Core plasmas respectively are being developed. The primary role of X-ray Survey [2] diagnostic is viewing the plasma core from an equatorial port for the identification and monitoring of impurities, because the X-ray spectral region (0.05 - 10 nm) contains important emission lines of light (Be, C, O) and metallic (Fe, Ni, Cu) impurities and strong emission features of likely plasma dopants (Ar, Ne, Kr). Edge spectrometer is to provide profiles of ion temperature (T_i)

and plasma rotation at the plasma edge from emission measurements in the wavelength range of 0.2-0.5 nm.

A Fixed Cu target X-ray source is being designed at ITER-India. Later more targets like Ni, Cr, SS and W will be used to cover the entire required wavelength range. The source comprises a line filament as an electron source and Cu anode as a fixed target and allows X-ray beam output through a thin Be window. It will be operating at varying applied potentials up to 30 kV.

Monte Carlo simulations have been done to evaluate the performance of the X-ray source, to obtain information on output photon spectra, flux and dose rate at the detector location, 110 mm from the Cu target. The operational output dose rate was obtained as 6.7Sv/hr for a net photon flux of 3.3×10^{10} /s/cm^2. For safety purpose the leakage dose rate from the X-ray source was also calculated and the obtained value is around 0.26μSv/hr at a distance of 5cm from the steel chamber, which is in good agreement with the ALARA limits specified by AERB for radiation safety.

This presentation includes the description of the ITER X-ray crystal spectrometers, design requirements for the X-ray source needed for the testing and calibration of the spectrometer and the simulation results of the X-ray beam characteristics.

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Charge Exchange Recombination Spectroscopy modeling challenges on MST

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Modeling Charge Exchange Recombination Spectroscopy (CHERS) measurements on MST has addressed a number of unique challenges. For typical discharges, the emission from electron-impact excitation is comparable to the charge-exchange emission induced by our 5 Amp, 50 kV diagnostic neutral beam. As such, isolating the charge exchange emission entails modeling both a view intersecting the beam and a view of the background plasma. This modeling requires detailed calculations using the Atomic Data and Analysis Structure (ADAS) database since the Doppler broadening of common emission lines, like C VI at 343.4 nm, is comparable to broadening due to spin-orbit coupling effects which separate the fine-structure components of the otherwise degenerate states for the n=7 to n=6 transition. A final complicating factor in the analysis is the competition of emission strength from different impurities with similar atomic structure. The atomic structure of C^{+5} with its single electron in a highly-excited state looks very similar to O^{+5} with an electron in a highly-excited state resulting in emission at nearly identical wavelengths. Since the cross section for O VI emission at 343.4 nm is much larger than that for C VI, the background emission tends to be dominated by oxygen which has a different fine-structure distribution than carbon. Hence, the fine-structure populations for both species are calculated in ADAS and incorporated into the fitting model used to analyze CHERS data on MST to determine core ion temperature and flow velocity.

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Coronae of stars with super-solar elemental abundances

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Coronal elemental abundances are known to deviate from the photospheric values of their parent star, with the degree of deviation depending on the First Ionization Potential (FIP). This study focuses on the coronal composition of stars with super-solar photospheric abundances. We present the coronal abundances of six such stars: 11 LMi , iota Hor, HR 7291, tau Boo, and alpha Cen A and B. These stars all have high-statistics X-ray spectra, three of which are presented for the first time. The abundances measured in this paper are obtained using the line-resolved spectra of the Reflection Grating Spectrometer (RGS) in conjunction with the higher throughput EPIC-pn camera spectra on board the XMM-Newton observatory. A collisionally ionized plasma model with two or three temperature components is found to represent the spectra well. All elements are found to be consistently depleted in the coronae compared to their respective photospheres. For 11 LMi and tau Boo no FIP effect is present, while iota Hor, HR 7291, and alpha Cen A and B show a clear FIP trend. These conclusions hold whether the comparison is made with solar abundances or the individual stellar abundances. Unlike the solar corona where low FIP elements are enriched, in these stars the FIP effect is consistently due to a depletion of high FIP elements with respect to actual photospheric abundances. Comparing to solar abundances (instead of stellar) yields the same fractionation trend as on the Sun. In both cases a similar FIP bias is inferred, but different fractionation mechanisms need to be invoked.

Investigation Of The Role Of Neutrals In Edge Transport Barriers Using Pmt Array Based Spectroscopic System In Aditya Tokamak

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In magnetically confined fusion plasmas, the transition from a low energy confinement state (L mode) to a higher energy confinement state (H mode) is characterized by the formation of a transport barrier at the plasma edge. For achieving reactor relevant plasma conditions, it is very important to understand the physics of the formation, sustainment and destruction of these edge transport barriers. Several experiments have indicated that fuel neutrals play an important role in formation, sustainment and destruction of edge transport barriers. Consequently, understanding the physics of barrier formation necessitates detailed measurement of neutral profiles in presence and absence of barriers with high spatial and temporal resolution. Radial profiles of H_α with high temporal and radial resolution have been measured in low and improved confinement discharges of Aditya tokamak to explore the role of neutrals in formation/destruction of edge transport barriers using Photomultiplier tube (PMT) array based spectroscopic system. The PMT array module incorporates 8 PMTs, which provides high gain, high sensitivity, wide dynamic range, fast time response & high S/N ratio. Light collected from 8 different vertical chords spanned over the poloidal cross-section in the low-field side edge region of the plasma is fed to the PMT array through a narrow band-pass H_α filter having center wavelength at 656.3 nm with 1 nm bandwidth. The chord-integrated data is inverted using Abel-like matrix inversion technique to obtain the radial profiles of neutrals. In this paper, the variation of profile sharpness and their penetration characteristics in low and improved confinement discharges will be presented.

Mid-pressure Ar/N_2/H_2 RF discharge characterisation

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Low-temperature nitrogen containing plasmas are used in numerous applications e.g. for surface functionalization, nitriding etc. Often argon is used as the buffer gas as excited states of argon can actively participate in the production of nitrogen reactive species while quenching of these species by Ar is orders of magnitudes smaller. It has been found that addition of hydrogen to Ar / N_2 mixture increases the concentration of both excited nitrogen and hydrogen atoms in the plasma, prevents target surface oxidation and thus enhances nitritation efficiency [1].

The aim of present work was electrical and spectroscopic characterisation of Ar /0-5% N_2/ 1% H_2 RF mid-pressure discharge. The discharge was ignited in quartz tube at 20 Torr pressure and at a total gas flow rate of 60 SCCM with the help of a 40 MHz generator. The electrical characteristics were recorded with oscilloscope TDS-540B. Time averaged spectra belonging to the discharge region between electrodes were recorded with spectrometers Ocean Optics 4000, MDR-23 and Andor Michelle from lateral direction of the tube.

On the basis of registered current, i, voltage, u, and phase shift between them, φ, the voltage on the plasma, $u_{PL}=u\cdot\cos(\varphi)$ and input power, $P=i\cdot u\cdot \cos(\varphi)$ were calculated. At used currents (0.01-0.1 A) the current growth caused only a small decrease of the plasma voltage. The plasma voltage was lowest for pure Ar (30-40 V), and highest for Ar / 5% N_2 / 1% H_2 (160-180 V). Input power increased with the current and N_2, H_2 concentration in the mixture. For pure Ar it remained in the range 0.2-2 W while for Ar / 5% N_2 / 1% H_2 it was 2-10 W. Electric field strength in the plasma column, E_{PC} , was found for Ar and Ar/5% N_2 mixture as slope of the dependence u_{PL} = f(L), where L is the distance between powered and grounded electrode. At current i=0.06 A in the case of pure Ar E_{PC}= 3.1 V/cm while in the mixture of Ar / 5 % N_2 E_{PC}= 15.6 V/cm.

The gas temperature was determined on the basis of N_2(C-B,4-2) rotational spectra at 295 nm. In our experimental conditions the temperature increased from 430 K (pure Ar) up to 600 K (Ar / 5 % N_2 / 1% H_2). N_2(C) vibrational temperatures were determined on the basis of Boltzman plot of N_2(C) vibrational transitions 3-5, 4-2. At constant input power, P=2 W the vibrational temperature changed from 5000 K (Ar / 0.5% N_2) up to 6500 K (Ar / 5 % N_2 / 1% H_2). Density of Ar atoms in 1s states was determined by method which utilizes the reabsorption of photons in plasma [2]. In Ar plasma at P=3W the densities were $[Ar(1s_5)] \approx 5\cdot10^{12}$ cm^{-3}, $[Ar(1s_{2,4})] \approx 1\cdot10^{12}$ cm^{-3} and $[Ar(1s_3)] \approx 7\cdot10^{11}$ cm^{-3}. In Ar/N_2 plasma, the bands of N_2 FPS interfered with Ar lines and did not allow reliable determination of [Ar(1s)].

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4f and 5p inner-shell excitations of W-W^{3+} ions

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Tungsten should be an important diagnostic for the presence of heavy atomic species in the ITER plasma [1]. Understanding the influence of W on ITER plasma requires detailed knowledge about atomic structures and processes of tungsten atoms in all stages of ionization. In past years, the researches on the spectra of low ion stages of tungsten were much fewer than those of intermediate and highly ionized stages of tungsten, in spite of their importance at the edge region of ITER plasma. Since Haensel et al [2] firstly reported the photoaborption spectrum in the EUV energy region of the 5d transition metal W, Costello et al[3] and A Müller et al[4] also reported on dual laser plasma (DLP) experiments with atomic tungsten and on photoionization experiments with W^{q+} ions in charge states up to q = 5, respectively.

Here, with the purpose of theoretical simulation on the 4f and 5p inner-shell excitations of W-W^{3+} ions, calculations were performed with the Cowan RCN, RCN2 and RCG suite of Hartree-Fock with configuration interaction codes. Figure 1 shows the comparison between experiments and theoretical contributions of 4f and 5p inner-shell excitations of W-W^{3+} ions. It is clearly seen that two broad and strong resonances in the experimental spectra have been theoretically identified mainly from 5p-5d resonance. The 4f-5d,6d and 5p-6d transitions also have a small contribution to each spectrum, which are superimposed on the 5p-5d transition arrays. In this figure, two strong and broad absorption features from the 5p-5d resonance of W-W^{3+} ions are obviously observed. The distinct separation of the 5p excitations into two groups of dominant resonances can appear as a result of the spin-orbit splitting of the 5p hole.

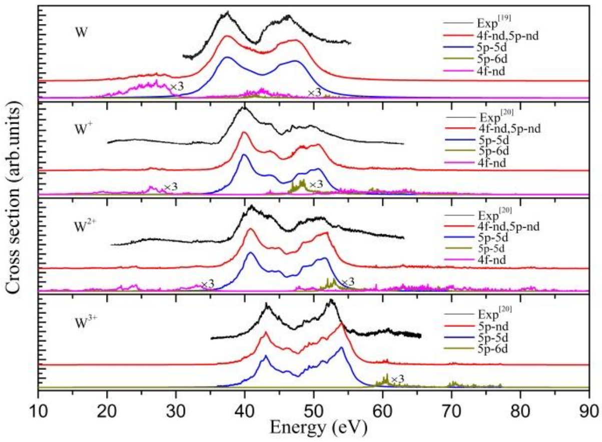

Figure 1. Comparison between experimental measurements and theoretical contributions of 4f and 5p inner-shell excitations of W-W^{3+} ions.

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Doppler Shift Spectroscopy Diagnostic for Indian Test Facility (INTF).

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India Test facility (INTF) is being commissioned in Institute for Plasma Research (IPR) to test ITER Diagnostic Neutral Beam (DNB) with full specification. Neutral beam system for INTF is based on a negative hydrogen ion source. The ion source is expected to deliver 60A negative hydrogen ion beam current of energy 100keV. The source will be operated with 5Hz modulation having 3s ON/20s OFF duty cycle for 3600s. To characterize the beam parameters several diagnostics will be used. One of them will be the Doppler shift spectroscopy (DSS), which will be used to measure the beam energy, line integrated beam uniformity, beam divergence, and neutralization losses inside the accelerator (stripping losses). The red shifted Doppler radiation emitted by the beam particles can be spectrally discriminated from background neutrals and then used for determining the beam energy and divergence of the beam itself and also the stripping losses. DNB ion beam is made of 1280 beamlets arranged in 4×4 beamlet groups each having matrix of 5×16 beamlets of diameter ~14mm. Total 36 LOS both from horizontal and vertical directions has been provisioned in the INTF system to map the beam of size ~ (0.6m×1.6m) completely. Port view angle with respect to the beam has been optimized to 60 degree for clear peak resolution from the background H-alpha radiation (~ 656nm). Due to the conductance limitation inside the extractor system of the ion source, pressure is relatively higher at that location and collision induced negative ion stripping (losing loosely bound electrons from the negative ion) is expected to be more at that region. As a result a fraction of negative ions will unable to get full energy before it gets neutralized by the stripping collisions. Therefore, a separate broad Doppler shifted peak corresponds to the extraction potential is expected along with the full energy peak corresponds to acceleration potential. The system is designed to resolve peak due to stripping losses from the full energy peak. Accuracy of about 9-10% is expected in the measurements of beam divergence from the present DSS design. The radiation collected by collimation lenses through viewports on the INTF vacuum vessel will be transmitted through optical fibers to the instruments, which are in air Czerny Turner (CT) spectrometers coupled to 2D CCD cameras. Optical throughout/etandue (light collection cone) and its propagation along the light transmitting path has been maintained as close as possible for the light collection optics and that of the spectrometer. A CT spectrometer coupled to a 2D CCD camera is a cheap and compact solution when dealing with acquisition of multiple lines of sights. To improve read out time defining some macro pixel (binning technique) is proposed. The design of the present DSS system is reported with background design considerations and calculations.

Emission signal enhancement in double-pulsed laser induced plasma on collinear geometry

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Laser induced breakdown spectroscopy (LIBS) has a great potential in a broad field of analytical and specialized application, compared with other spectrometric methods [1], the sensitivity of LIBS is poor, and matrix effect sometimes restrict LIBS application for quantitative analysis, therefore, strengthening of the LIBS signal in analytical samples is thus the natural objective of the present detection. In order to advance signal detection capability and to increase the sensitivity of LIBS, double-pulsed (DP) LIBS has been investigated in order to address these problems. Collinear DP LIBS is better in terms of industrial applications due to the simple optical alignment; therefore, investigation to emission enhancement mechanisms in this geometry configuration can give the optimal parameters for improving the sensitivity of DP LIBS.

Time- and spatial-resolved LIBS technique was used for investigating the plasma characteristics in aluminum-based alloys. Q-switched Nd:YAG lasers at 1064 nm wavelength have been employed to generate laser-induced plasma on aluminum-based alloys by SP and DP LIBS schemes. Time and spatial evolution of the plasma temperature and electronic density were investigated in these two schemes. The line intensity enhancements were investigated; a relation between increases in intensity and excitation energy level was established. Moreover, In our experimental condition, we found that the second plasma production was important in DP experiment on collinear geometry, meanwhile, we found that two sequential laser pulse with a certain delay time made the plasma to become more inhomogeneity and optical thick. To assess DP LIBS performance in analysis, the calibration curves for some elements present in alloy were established.

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High resolution spectroscopic measurements of edge plasma rotation and ion temperature in L- and H- modes at the COMPASS tokamak

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Properties of spectral lines radiated by fusion plasma impurities can be used to measure plasma rotation and ion temperature. Knowledge of both quantities is important for studying physics of L-H transition in tokamak plasmas. The change of poloidal rotation velocity seems to be interlinked with increased confinement in H mode, which can be shown on the evolution of the ion temperature in the plasma edge. In the COMPASS tokamak, carbon is among the main plasma impurities in connection with the installed carbon protection tiles. This makes the CIII lines, with wavelength around 465nm, good candidates for measurements of the edge plasma poloidal rotation and ion temperature. Such measurements are possible with the use of the two-grating spectrometer allowing for the wavelength resolution of 0.003nm. In this work the high-resolution spectroscopic measurement system installed at COMPASS is described. An analysis of a number of experiments is performed to study the evolution and the dependence of the edge plasma poloidal rotation and ion temperature on main plasma parameters as well as on the confinement mode.

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Preliminary Observations Of X-Ray Transitions From Middle Charged Tungsten Ions On Shanghai Ebit

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Tungsten has created great interest in spectroscopy as it is a hopeful candidate for the plasma facing material in future Tokamaks like ITER. Much effort is being made by various groups to provide spectroscopic data for W in many charge states and over wide spectral regions [1]. As a very high resolution X-ray spectrometer has been built in JET and has made a lot of observations, and JET has equipped divertors made by tungsten[2], which would be the same with ITER’s, we started to devote much time and effort on the X-ray observations of tungsten on Shanghai EBIT[3].

In the recently work, we aligned a flat crystal spectrometer[4] to an observation window of Shanghai EBIT. The energy of electron beam of Shanghai EBIT could smoothly cover a range from 1keV to 150KeV, and the flat crystal spectrometer could reach at least more than 3000 resolving power. This is an ideal facility set for studying the X-ray spectroscopy of middle charged tungsten ions.

Using this setup we have made several measurements of tungsten spectra in the region around 5.0 Å to 6.0 Å for different electron beam energies. Systematic calculations of the atomic structure giving rise to such transitions were done. A preliminary identification of tungsten spectral lines was done by comparing the spectroscopic data obtained in our experiments with the calculation results. But further confirmation of these data is still required and after that the confirmed data can be published.

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Optical spectra of plasma-streams and plasma from targets in plasma-focus experiments

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The paper reports on the selected results of optical emission spectroscopy of free plasma streams generated within the modified PF-1000U machine, and plasmas produced during interactions of such streams with different solid-state targets. The PF-1000U experimental chamber was filled up with pure deuterium at the pressure p_o = 1.6 or 2.4 mbar. When the use was made of the gas-puffing valve, located at the symmetry axis, behind the central opening in the inner electrode, there was injected additionally about 1 cm^3 of deuterium at a pressure of 2 bars. This gas-puffing was initiated 1.5 or 2 ms before the main discharge ignition. The investigated plasma discharges were supplied from a condenser bank charged to U_o = 23 kV (W_o = 352 kJ), and the maximum discharge current amounted to about 1.8 MA. In order to investigate a free-propagating dense plasma stream, the use was made of an optical emission spectroscopy (OES) technique. An optical collimator was situated side-on the vacuum chamber and coupled through an optical-fiber cable with a Mechelle®900 spectrometer. The optical spectra in the visible radiation (VR) range were recorded at a distance of 9 cm from the electrode outlets. Temporal changes of those spectra were compared for shots without and with the gas-puffing [1], and electron density was estimated from an analysis of the D_α-line profile, taking into account a linear Stark-effect. For discharges without gas-puffing the maximum electron density was about 1×10^{18} cm^{-3}, and for discharges with the gas-puffing it amounted to 2×10^{18} cm^{-3}. A comparison of the recorded spectra enabled the optimal operation mode of the PF-1000U facility to be selected.

The OES technique was also applied for studies of plasma produced from tungsten (W) and silicon-carbide (SiC) targets irradiated by plasma streams at a chosen distance from the PF-1000U electrodes ends. Measurements performed during interactions of plasma streams with the W-samples showed many WI and WII spectral lines [2], but their quantitative analysis was impossible because of overlapping. OES measurements were performed also for a SiC target [3], and produced impurity lines were identified, e.g. Si- and C-lines. In those cases the electron density was estimated from the D_α-line only, because D_β-line showed strong re-absorption effect. An analysis of temporal changes in the recorded optical spectra enabled to estimate dynamics of the target erosion. Structural changes upon surfaces of the irradiated targets were also analyzed by means of a scanning electron microscope (SEM) and the energy dispersive X-ray spectrometer (EDS).

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