Gerd Fußmann

PLASMA PHYSICS at the Humboldt-Universität zu Berlin

Plasma-material interaction studies and investigation of highly charged ions is the major field of activity in the plasma physics group at the Humboldt-Universität zu Berlin. Two experimental facilities are being operated: The linear plasma generator PSI-2 and an electron beam ion trap (EBIT) device. EBIT produces and stores highly charged ions of up to the heaviest elements in the periodic table. The scientific emphasis of the EBIT is on atomic physics research and applications to fusion-relevant hot plasmas. The PSI-2 generator is a stationary source producing plasmas with parameters very close to the conditions in the boundary region of nuclear fusion devices. The project focuses on basic plasma physics, development and experimental testing of diagnostic components, plasma-material interaction, and material characterization. This article gives an overview of the two facilities and the research projects including results from recent X-ray spectroscopic measurements and chemical erosion.

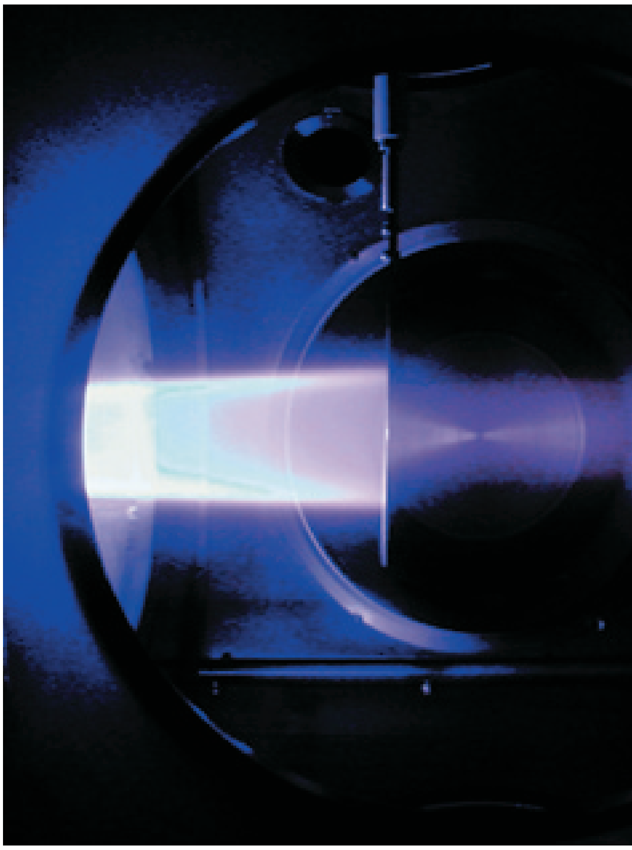
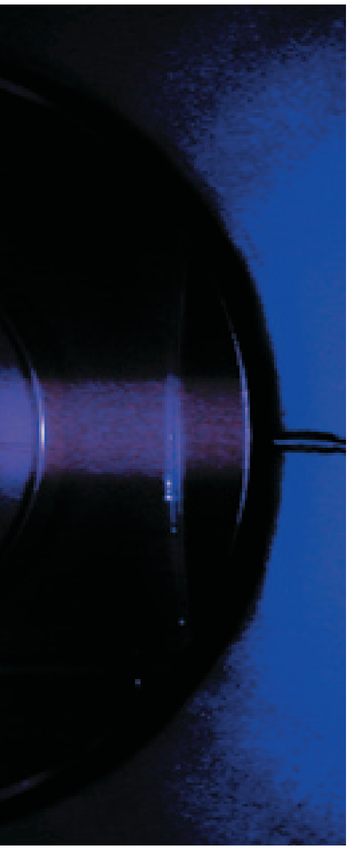


Fig. 1
Photograph showing the shining plasma column in front of the neutralizer plate.

A hot gas in which the atoms are dissociated into positive ions and negative electrons is called a *plasma*. Plasmas cover an extremely wide range of densities and temperatures and exist in astrophysical objects such as stellar interiors and atmospheres or gaseous nebulae. In our everyday lives there are many applications of plasmas which benefit from the specific properties of the plasma state. Among these are such practical developments as light sources and the vast field of material processing for example plasma etching or surface hardening. The major recent interest in plasma physics originates from controlled thermonuclear fusion. Nuclear fusion is the energy source of all stars in the universe and one way to achieve fusion on earth is to create a plasma of deuterium and tritium particles with temperatures in the order of 100 million degrees. The problem of heating and containing such a plasma in laboratory devices has instigated large research effort over the past decades and the intention is to build a fusion reactor based on either the *tokamak* or the *stellarator* concept. Both are magnetic confinement systems whereby the plasma particles are confined to a toroidal region. Of particular importance for a reactor is control of the heat load on the plasma-facing components in order to limit erosion and impurity production to a tolerable level. The selection of the wall material is an essential issue in this context. New materials with improved heat flux acceptance and erosion behaviour are to be identified and characterized under plasma interactive conditions.

The research conducted by the plasma physics group at the Humboldt-Universität zu Berlin is at large aimed at supporting this effort. Previously the group belonged to the Berlin Branch of the Max-Planck-Institut für Plasmaphysik (IPP) and was associated to the University in 2004. Two experimental devices are operated: The plasma generator PSI-2 and the electron beam ion trap (EBIT).

Plasmaphysik an der Humboldt-Universität zu Berlin
Schwerpunkt der plasmaphysikalischen Aktivitäten an der Humboldt-Universität zu Berlin sind Studien zur Plasma-Wand-Wechselwirkung und Untersuchungen an hochgeladenen Ionen. Zu diesem Zweck werden zwei eigenständige Experimente betrieben: der Plasmagenerator PSI-2 und eine Elektronenstrahl-Ionenfalle (EBIT). Mit der EBIT kann praktisch jedes beliebige Element des Periodensystems in hohe Ladungszustände überführt und für die Analyse gespeichert werden. Das Spektrum der Arbeiten an der EBIT erstreckt sich von atomphysikalischen Untersuchungen bis zu Anwendungen auf Hochtemperatur-Fusionsplasmen. Der PSI-2 Generator ist eine stationäre Quelle, mit der ähnliche Plasmen wie im Randbereich von Fusionsexperimenten erzeugt werden können. Die Untersuchungen am Plasmagenerator konzentrieren sich auf grundlegende plasmaphysikalische Fragestellungen, auf die Entwicklung und Erprobung von diagnostischen Methoden und Komponenten, auf Studien zur Wechselwirkung von Plasmen mit Festkörperoberflächen sowie auf die Charakterisierung von Materialien nach Exposition im Plasma. Im vorliegenden Beitrag wird ein Überblick über die Experimente und bearbeiteten Projekte gegeben. Beispielhaft wird auf unsere spektroskopischen Studien im Röntgenbereich und auf Untersuchungen zur chemischen Erosion von Kohlenstoff eingegangen.



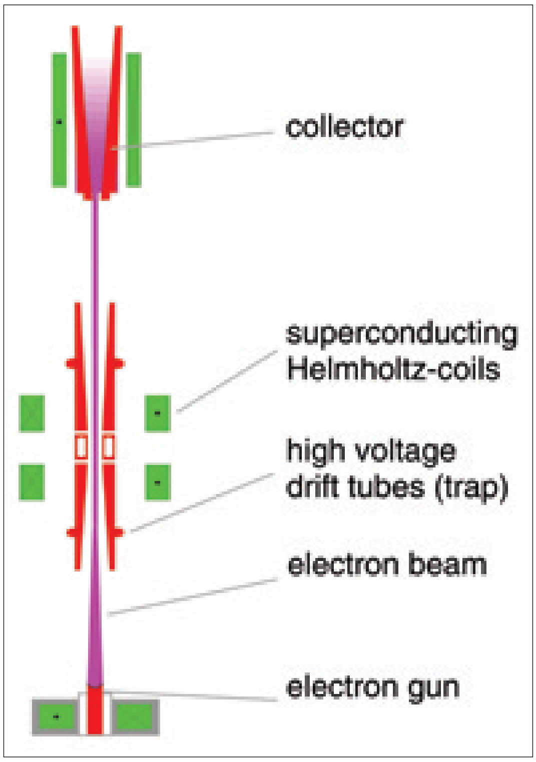
The PSI-2 generator is in essence a high current arc discharge where a steady-state plasma is produced between a heated cathode and a hollow anode. The plasma is confined by a magnetic field and guided into a target chamber for diagnostic measurements or plasma- surface interaction studies. A neutralizer plate is located at the end of the generator to terminate the plasma in the axial direction (Fig. 1). In the target chamber a long, large-volume (V=10 l) magnetized plasma column is achieved with parameters (temperature and density) very close to the conditions existing in the boundary region of fusion devices. Major topics of investigation at PSI-2 are: basic plasma physics (rotation and flow behaviour of the magnetized plasma, turbulent plasma fluctuations, particle and energy transport), plasma diagnostics (probe measurements and spectroscopy), and plasma-wall interactions (erosion of graphite-based materials, deposition and erosion of hydrocarbons on heated surfaces).

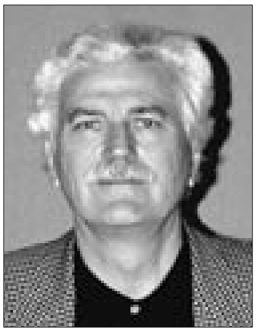
The electron beam ion trap EBIT is a device for producing, confining and studying highly charged ions. Highly charged ions are particularly important in X-ray astrophysical observations and fusion experiments where the radiation from the ions can be used as a means to diagnose the temperature or density of the plasmas. Further, such radiation from tokamak devices can provide information on the transport and the spatial distribution of impurities. To produce highly charged ions EBIT employs a monoenergetic electron beam which is accelerated and compressed by electric and magnetic fields. The beam originates from an electron gun, travels along the central axis of three cylindrical drift tubes, and is dumped on the walls of a collector electrode (Fig. 2). The trap is formed by the field of the electron beam's space charge attracting positive ions in the radial direction and the geometry of the drift-tube assembly provides axial trapping. Atoms injected into the trap are ionized successively within the beam by electron collisions. The resulting highly charged ions can then be observed through X-ray, UV or visible spectroscopy. Our emphasis at EBIT is on atomic physics research (atomic structure measurements, tests of quantum electrodynamics), applications to hot plasmas (spectral line diagnostics, rate coefficients and cooling rates), and basic plasma physics (ion confinement in traps and magnetized plasmas).

Radiative cooling rates of highly ionized krypton ions

As part of our program to carry out spectroscopic research in support of the fusion work, the EBIT has been used to measure the radiative cooling rates for highly ionized species of krypton. Krypton has recently been proposed as a coolant for the plasma edge region of future large tokamaks, such as the International Thermonuclear Experimental Reactor (ITER) and in order to predict the effect of krypton puffing on the performance of the fusion plasma, knowledge of accurate radiative cooling rates is required. To determine the cooling rates, we used a technique where a steady-state ion population in EBIT is probed by fast scans of the beam energy. This is demonstrated in Fig. 3, a plot of the radiation pattern of a population of krypton ions approaching the ionization balance of a plasma at an electron temperature of about 50 million degrees. The plot was generated by probing the ions over 20 ms in a 900–15000 V scan interval. During the scan the beam

Fig. 2
Schematic of the electrodes and magnets of the EBIT.





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Born 1942. Study of physics at Universitiy in Darmstadt and Bochum, diploma and doctorate Bochum (1974). Prize of the Ruhr University Bochum (1975). Scientific staff of IPP Garching (1975–1992), guest stay in England (JET, 1987), lectures at Augsburg University, Habilitation in physics at University Augsburg, Full Professor at the Humboldt-Universität zu Berlin, Professorship in Experimental Plasma Physics (1993), Director und Scientific Member at the Max Planck Institute for Plasma Physics (since 1993). Co-editor of the magazine *Contributions to Plasma Physics*. Speaker of the DFG-Board on *Optics, Molecules, Atoms and Plasma.*

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energy and the X-ray energy for each X-ray detected were recorded. Each electron-ion interaction which leads to the emission of X-ray photons leaves its fingerprint in the plot. 17 different interaction processes can be resolved in Fig. 3, including impact excitation by electron-ion collisions and electron-ion recombination (resonant and non-resonant). Channel-specific cooling rates were determined from the measurements by weighting the data with the electron-energy distribution of a plasma. We have compared our measured cooling rates with the values predicted by different theoretical models. It turns out that the calculations underestimate the cooling effect of krypton by as much as a factor of two.

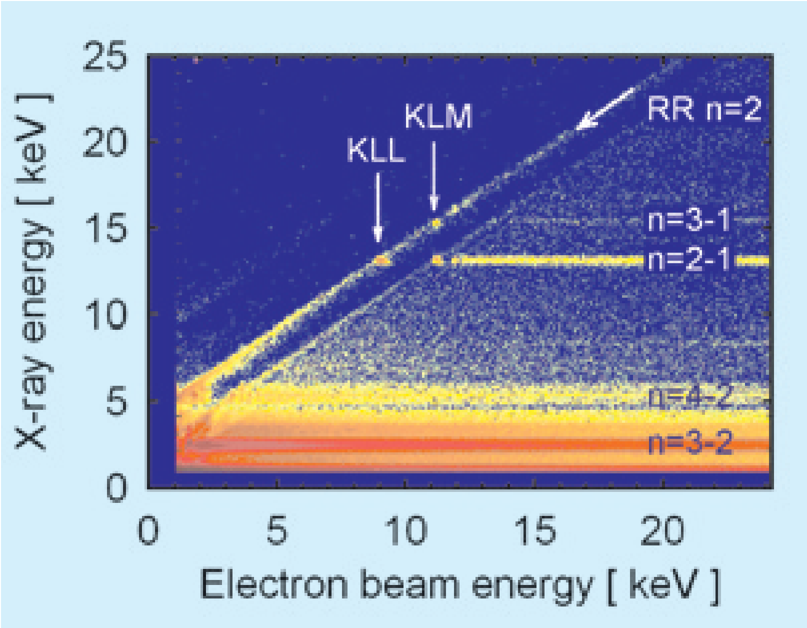

Fig. 3
Scatter plot of X-rays from krypton ions as a function of the electron-beam energy.

Chemical erosion of carbon

Chemical erosion of graphite and carbon-based materials is a plasma-surface process which results in hydrocarbon emission in fusion experiments. Hydrocarbon emission can then lead to the formation of hydrocarbon films which presents a serious problem because the amount of tritium in these layers could become large. Knowledge of the yield of chemical erosion is thus crucial, specifically in selecting a target or wall material for ITER. With the PSI-2 plasma generator we have measured the chemical erosion yield of various carbon fibre composites (CFC). The CFC samples were exposed to hydrogen and deuterium plasmas and the main emphasis was on the question of whether the erosion is dependent on the ion flux density. Starting with low and moderate flux densities (10^{21} ions/m^2 s) each hydrogen ion hitting the sample has a chance of nearly 10% of releasing a methane (or some other carbon-consisting) molecule from the surface. Raising the flux density progressively decreases the yield. For $2x10^{23}$ ions/m^2 s, a substantial and most favourable reduction in the erosion yield to values of about 0.5% is found (Fig. 4). This is a highly appreciated property in view of the large fluxes in ITER or in a fusion reactor.

Fig. 4
Chemical erosion yield of two CFC composites as a function of particle flux density.