Preface for the special topic on "ion source diagnostics"

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There are a huge variety of ion source types employed to produce charged particle beams for discovery physics and accelerator applications (e.g., neutral beam heating of thermonuclear fusion plasmas, ion beam analysis of material surfaces, and spallation neutron sources). The requirements for ion sources, such as the ion species, beam current and energy, and beam quality, are equally diverse. For example, the large-area neutral beam injection ion sources are expected to produce 40 A of negative deuterium ions with a 1 MeV beam energy, whereas charge breeder ion sources produce sub-microampere radioactive element beams for fundamental nuclear physics experiments. What is common to all ion sources is the need for diagnostics to quantify their performance and develop them further. There are always development goals to increase beam current, purity, and quality. The ion source stability, reliability, and maintenance interval can always be improved as can the simplicity of the mechanical design and user-friendliness. Furthermore, ion source diagnostics provide insight into source behavior by spatially and temporally measuring the plasma parameters.

The intention of this Special Topic is to describe the diagnostic methods used for ion source development, operations, and monitoring in continuous use and to bring these diagnostics to the attention of all involved in ion source development. The issue consists of 15 review papers covering diagnostics of ion sources intended for neutral beam heating, accelerator injection, and other applications. The selected topics offer a cross section of ion source diagnostics applied to negative and positive ion sources, highlighting similarities of the diagnostic needs and individual diagnostic challenges pertaining to specific types of ion sources. The contributions focus on microwave sources, RF-driven sources, and arc discharges with the intention to encourage investigations on all other source types. All contributions have an experimental focus, some of them supported by discussion on theory and modeling. The selection of contributions emphasizes the role of diagnostics within the ion source (i.e., plasma parameters and surface processes) rather than beam diagnostics as the key to understand the underlying physics required to optimize the ion source performance.

In practice, the most fundamental diagnostic of the ion performance is the intensity and quality (purity, emittance, etc.) of the extracted beam. Thus, the special issue does include a contribution by Kalvas, reviewing the most fundamental beam diagnostics, namely, the measurement of the ion beam intensity and phase space distribution.[1] The paper describes both destructive and non-destructive diagnostics of continuous and pulsed ion beams across a range of beam currents and sizes from amperes to individual ions requiring vastly different apparatus, e.g., calorimeters or particle multipliers. Techniques to measure the phase space distribution of the ion beam, most relevant for accelerator ion sources, are also explained.

The contributions related to negative hydrogen ion sources focus on large and multi-aperture sources to achieve high currents for the neutral beam injection of magnetic fusion devices. As these sources need to operate at low pressures, the formation of sufficient negative hydrogen ions relies on the surface mechanism, for which cesium is evaporated into the source to lower the work function. Insights into the surface formation of negative hydrogen ions are presented by Wada, starting with a review of work function measurement methods up to the correlation of the work function with the negative ion yield and the diagnostics of the surface condition in the plasma environment.[2]

A very general and versatile plasma diagnostic tool being non-invasive to any ion source is emission spectroscopy. The contribution by Wünderlich *et al.* gives the overview on its capabilities covering the wavelength range from ultraviolet to infrared spectroscopy with a focus on the easily accessible optical wavelength range.[3] Spectroscopic instrumentation together with the analysis techniques is presented, offering a tool for process monitoring toward quantification of plasma parameters, both temporally and spatially resolved.

The window to knowledge of a manifold of plasma parameters obtained by a variety of diagnostic methods is opened with the contribution by Serianni *et al.*, introducing spatially resolved diagnostics for optimization of large ion beam sources.[4] The diagnostics of the prototype source for neutral beam injection of ITER and the large ion source used to generate a beam for diagnostic purposes of the fusion plasma are presented by Bandyopadhyay *et al.*[5] The characterization of the beam properties from the multi-aperture source (up to 1280 apertures for the ITER source) combined with a five-stage electrostatic acceleration system is addressed by Kashiwagi *et al.*[6]

The aspect of optimizing the RF-power coupling to the plasma and, thus, increasing the overall efficiency and reliability of the ion source is highlighted by Briefi *et al.*[7] Experimental measurements of the power transfer efficiency are complemented by diagnostics of the plasma parameters; both are accompanied by modeling efforts, thus opening the route to further optimization.

The contributions focusing on microwave-driven ion sources intended for the injection of high-current singly charged ion beams or multicharged heavy-ion beams into accelerators start with a contribution by Megía-Macías *et al.*, introducing time-resolved diagnostics of pulsed 2.45 GHz microwave-driven hydrogen discharges, similar to devices employed for high-current proton beam production at accelerator facilities.[8] The described techniques include optical emission spectroscopy [in visible and vacuum ultraviolet (VUV) wavelengths], Langmuir probes for the measurement of the plasma electron temperature and density, ultra-fast imaging of the discharge at the breakdown transient, and ion species measurements with the velocity filter and ion mass spectrometer.

Another example of pulsed positive ion plasma diagnostics is presented in the contribution by Skalyga *et al.*, reviewing techniques applied for studying so-called gasdynamic ECR ion sources.[9] The gasdynamic ion source plasma is sustained by high-frequency radiation from a gyrotron, resulting in very high plasma density, which not only limits the applicable diagnostics but also opens the door to techniques such as the measurement of Stark broadening to deduce the plasma density. The contribution of Skalyga *et al.* introduces the concept of kinetic instabilities, which often limit the ability of ECR ion sources to produce high charge state ions.

Diagnostic techniques for the study of instabilities are elaborated on by Toivanen *et al.*, focusing on a continuous and pulsed operation mode of a minimum-B ECR ion source.[10] The advantages and disadvantages of different instability detection methods and the impact of the non-linear plasma processes on ion source performance are described. The reviewed techniques include the measurement of microwave emission and bremsstrahlung bursts and temporal fluctuations of the plasma potential and particle (electron and ion) currents. The paper highlights how modern diagnostic methods can provide new insights on the physics explaining semi-empirical scaling laws applied to the ECR ion source design for decades and how two-frequency heating can suppress the instabilities.

The stability of a high-frequency ECR discharge and the extracted beam depends on the electron energy distribution of the confined electrons. Izotov *et al.* described a technique to measure the energy distribution of the electrons escaping the confinement and how it can be used for deriving the energy distribution of the confined electrons.[11] The paper highlights the non-Maxwellian nature of the electron energy distribution, which complicates the diagnostics and definition of the plasma parameters of ECR ion sources, and underlines the different challenges met in the diagnostics of low temperature discharges and plasmas containing high energy electrons and high charge state ions.

Bremsstrahlung and x-ray diagnostics of ECR ion sources outlining their significant contribution in understanding the electron heating and confinement properties of ECR plasmas where invasive diagnostics techniques cannot be applied are described by Thuillier *et al.*[12] The paper summarizes the main results, which have paved the way for the development of modern (superconducting) ECR ion sources, and discusses the challenges in interpretation of the bremsstrahlung and x-ray spectra. The contribution goes beyond reporting on the measurement of time-averaged emission spectra by introducing techniques for time-resolved bremsstrahlung diagnostics and the state-of-the-art spatially resolved CCD-imaging of the ECR discharge.

Microwave-based diagnostics of ion source plasmas are becoming increasingly popular. The methods explained in the paper by Mascali *et al.* include microwave interferometry and microwave polarimetric techniques, intended for the non-invasive measurement of the plasma density.[13] The paper highlights the necessity of combining various methods, such as microwave techniques, optical emission spectroscopy, and spatially resolved x-ray measurements, for the diagnostics of high charge state ion source plasmas.

Multiple frequency heating is a well-known technique to enhance the beam currents extracted from high-frequency ECR ion sources and the stability of the discharge. The contribution by Vondrasek summarizes experiments on multiple frequency heating, highlighting the usefulness of the method for diagnostics of ECR ion sources.[14] The paper discusses the diagnostic needs, required to explain conclusively how multiple frequency heating acts on the ion source plasma parameters.

The diagnostics of charge breeder ECR ion sources highlighting the differences in the beam current measurement between charge breeders and stable isotope ion sources are reviewed by Maunoury *et al.*[15] The method of charge breeding, namely, the injection of the beam of singly charged ions, either stable isotopes (for development) or radioactive isotopes (for operations), offers a unique diagnostic opportunity using the transport and stepwise ionization of the injected ions to deduce the plasma parameters of the ion source. The diagnostics of charge breeder ion sources are supported by computer simulations, which are also described in the contribution.

The collection of review papers in this Special Topic highlight the importance of appropriate diagnostics in the operation and development of the state-of-the-art ion sources. The overarching message is that further advances in ion source performance, deeper understanding of the underlying physics, and validation of novel ion source concepts require complimentary diagnostics. Many contributions describe how the diagnostic methods themselves could be developed to meet the experimental demands. We trust that this collection of review papers stimulates the exchange of ideas between diagnostic experts across the ion source community and serves as a "handbook" compiling the knowledge of ion source diagnostics otherwise dispersed in the existing literature.

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